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THE RELATION OF GEOLOGY TO MINING.[1]

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Geology was founded to a large extent on the observations of the miner. The primary geological conceptions, such as *outcrop, strike, dip, hanging-wall* and *foot-wall*,[2] together with a wealth of mineralogical and petrological detail, were furnished by the early metal-miner; while the close study of the bedding relations of the coal-seams, which their profitable extraction demanded, formed the basis of modern stratigraphy. Fournet writing on ore deposits in 1835 says:

"C'est a l'étude de leurs gisements, de leurs liaison avec les substances voisines et de leurs rapports avec certains accidents du sol encaissant, que la Geologie doit sa naissance."[3]

In such terms the earlier geologists acknowledged their debt to mining. But to-day the positions are reversed: mining is in debt to geology.[4] Thus, by the application of geological principles,

[1] Being the presidential address delivered to the Institution of Mining and Metallurgy at their annual meeting in London, on March 26, 1914.

[2] See the interesting Appendix to the English translation by Mr. and Mrs. Hoover of Agricola's "De Re Metallica," London, 1913, p. 603.

[3] "Études sur les dépots metallifères. Traité de Géognosie," A. Burat, Vol. III., p. 383, Paris, 1835.

[4] Cp. Knox (*Eng. and Min. Journ.*, Vol. 75, 1903, p. 849): "In the last ten years the professional geologists have shed more light on the fundamental problems of mining than has emanated from all other sources combined. It is impossible for the engineer to gauge accurately his debt to pure science, but if geology has done nothing for him except to clear his mind of superstition and false theory, great has been his work."

valuable seams and lodes, even when distributed by igneous intrusions or dislocated by faulting, are traced far beyond their first-known outcrops, and facts bearing on their downward extension are scientifically interpreted; while detailed geological surveys of mining districts are of the greatest service to prospectors, and sometimes lead to entirely new discoveries. To-day, on the great iron and copper mines of the United States, not only are geologists retained to study the deposits, but the exploratory work is often committed to their care. By means of a system of routine work, successfully organized on some of these mines, veins and ore-shoots are correlated from level to level; raises, cross-cuts and pump-stations are located in the positions most suitable to the geological conditions; and ore-bodies lost in faulted country are recovered, the fault displacement being determined quantitatively and allowed for in subsequent development work on lower levels.[1]

Specific instances of the successful application of geological knowledge to mining work can, of course, be given in abundance: but a few must suffice for the present purpose.

In England, the proving of the underground extension of the coalfields beneath the younger rocks surrounding them, is of paramount importance to its industrial welfare. One of the first pieces of work in this direction resulted from the admirable mapping of the Midland coalfield by Beete Jukes, a distinguished member of the Geological Survey of England and Wales. The entire correctness of his theories was demonstrated by Henry Johnson in a deep sinking at Sandwell Park, when the first definite proof was furnished of the prolongation of the south Staffordshire coalfield to the east under the fringe of overlying Red Rocks.

Similarly, the discovery of a buried coalfield in the southeast of England was the direct result of a piece of pure scientific deduction. Godwin-Austen[2] argued that the tectonic folds in the

[1] For excellent examples of such work see Linworth, "Applied Geology in the Butte Mines," *Trans. Amer. Inst. Min. Eng.*, 1913.

[2] Godwin-Austen: "On the Possible Extension of the Coal-Measures Beneath the Southeastern Part of England," *Quart. Journ. Geol. Soc.*, Vol. XII., 1856, p. 38.

Palæozoic floor, by which the existence of coal-basins are determined, would be traceable, even when covered by a great thickness of newer rocks; because a line of disturbance, whether of faulting or folding, when once established, tends to be the locus of subsequent movements and thus to set its mark on newer strata. The correctness of this tectonic principle was demonstrated by the successful borings, carried out in the neighborhood of Dover,[1] first by Sir Edward Watkin, and later by the Burr companies under the scientific advice of Professor W. Boyd Dawkins and other geologists. These borings showed that deeply buried under Mesozoic and Tertiary strata, is a coalfield, situated on the line connecting the seams worked in northern France and Belgium with those of south Wales and Bristol; and it appears not improbable that other coal-areas might be found, if the underground geology of this line of country were systematically explored. A satisfactory feature of the discovery of buried coalfields in England is the large addition thereby made to British coal-resources, as to which previous estimates had been rather pessimistic.[2]

Another instance of the successful application of geology to mining is furnished by the tracing eastward and southward of the sub-outcrop or apex of the Rand banket formation under a cover of up to 1,200 feet of later unconformable beds.[3] The investigations that led to this result were based on a geological survey of the country between Boksburg, the Springs and Heidelberg, the first results of which made it probable to me that the Van Ryn conglomerate, which disappears near the Springs beneath the Karroo coal-measures, and the Nigel conglomerate, emerging therefrom near Heidelberg, were geologically identical, although separated by a large area in which Dolomite and Coal-measures form the surface.[4] As my work progressed, the sup-

[1] M. Burr. "The Southeastern Coalfield: Its Discovery and Development," *Science Progress*, Vol. III., 1909, p. 379.

[2] First Coal Commission Report.

[3] Namely, the Dolomite with its basal Black Reef quartzites (Potchefstroom or Transvaal System) and the Beaufort or Ecca coal measures (Karroo System).

[4] "Gold Mines of the Rand," London, 1895, p. 17. A previous survey

position that the two outcrops with their opposed dips were respectively the northern and southern lips of a large but shallow synclinal basin, became almost a certainty; and deep borings made in the intervening country confirmed in the end the correctness of the theory in the most satisfactory manner.[1] The successful outcome of these investigations added to the Witwatersrand goldfield an enormous area of mining ground in which the banket is not too deep for exploitation, should its average gold-tenor prove high enough to enable it to be profitably extracted—a consummation, of course, devoutly to be wished but only demonstrable by shaft-sinking and development, since assay results of bore-hole cores are no guide to average values. The deepest bore-hole[2] of the series under my immediate supervision, namely, that put down on the boundary of the farms Grootvlei and Daggafontein, was practically on the axis of the syncline and cut the Main Reef at a depth of 5,540 feet (or corrected for deviation, 4,880 feet). It passed through 1,140 feet of Dolomite before entering the Witwatersrand formation, but gave a most instructive section of the latter, intersecting the Kimberley, Bird, Modderfontein and Van Ryn or Main Reef series of conglomerates and their associated quartzites, slates and sheets of amygdaloidal diabase. At the time of boring the whole of the core, about a mile in length, was carefully labelled and preserved on the property in a specially constructed core-house.

The limited time at my disposal will not allow me to recapitulate more than a few of the important services rendered in recent years to mining by geologists. But mention must be made of E. J. Dunn's survey of the Bendigo goldfields[3] and his brilliant exposition of the true nature of the remarkable saddle-reefs, whose

which I undertook at the instance of the late W. Y. Campbell had shown that the Van Ryn series of the eastern Rand was the representative of the Main Reef Series of the Central Rand. See also *Quart. Journ. Geol. Soc.*, 1897, pp. 82 and 83.

[1] Hatch, "The Extension of the Witwatersrand Beds Eastwards," *Trans. Geol. Soc. S. A.*, Vol. VII., 1904, p. 57.

[2] Total depth 5,582 feet, and thus the second deepest of the whole Rand.

[3] Dunn, "Report on the Bendigo Goldfield," Department of Mines, Victoria, 1893.

tectonic structure has determined a type of mine-development quite peculiar to that field.

Again, S. F. Emmons' monograph[1] on the structure and genesis of the Leadville silver-lead ores has been of enormous value to the Colorado miners, not a few of whom owe their success on that field to the predictions of the distinguished economic geologist whose recent demise we must all deplore. On the other hand the theory advocated by Emmons that the ores were derived from metals leached from the overlying porphyries and the consequent conclusion that the lower or White Limestone would prove unproductive have probably somewhat retarded the deeper development of the district. These lower horizons have since proved to be very productive as will be shown in the new monograph on the Leadville district now in preparation by the U. S. Geological Survey.[2] Emmons' researches on the deposits of silver-lead ore in limestone at Leadville incidentally led him to develop the theory of metasomatism, or replacement, as a prime factor in the genesis of ore-deposits. Of this more anon.

Another worker in the same field, and moreover a friend of Emmons and long a colleague on the United States Geological Survey, is George F. Becker whose classical studies on the famous Comstock lode and its high-temperature thermal springs, have done so much to demonstrate the close genetic connection between ore-deposition and vulcanicity.[3] Becker's monograph on the geology of the Comstock lode was issued in 1882, and in one of the opening chapters he pays a remarkable tribute to Baron Ferdinand von Richthofen, who examined the Comstock in 1865

[1] S. F. Emmons, "Geology and Mining Industry of Leadville, Colorado," U. S. Geol. Survey, Monog. XII. (with atlas), 1886. According to Boehmer (*Trans. Amer. Inst. M. E.*, Vol. 41, 1911) the Leadville deposits have produced gold, silver, lead, zinc and copper to the value of 350 million dollars in thirty years.

[2] "The Geology and Ore Deposits of the Leadville District." Written with the aid of the field notes and memoranda of the late S. F. Emmons by J. D. Irving.

[3] G. F. Becker, "Geology of the Comstock Lode and the Washoe District," U. S. Geol. Survey, Monog. III. (with atlas), 1882. According to Spurr (U. S. Geol. Surv. Prof. Paper 42, 1905, p. 270), the value of the total output of the Comstock Lode up to June, 1902, was 369.5 million dollars.

for the Sutro Tunnel Company, at that time engaged in driving a deep level adit to the lode at a depth over 1,000 feet vertical below the then-existing workings. The German geologist had a keen insight into structure, and although the mines were, when Becker wrote, about six times as deep as they were at the date of von Richthofen's report, the later investigator states that the opinions and predictions of his predecessor as to the behaviour of the lode in depth had been verified in a very remarkable manner.[1]

Von Richthofen ascribed both the filling of the Comstock fissure and the decomposition of the andesite "country" on its hanging wall to *solfataric action*,[2]—a term he used to describe the alterative influence of the gases and water-vapor given off from a late volcanic intrusion into the Comstock complex. Von Richthofen was evidently a strong supporter of Elie de Beaumont's theory of ore deposition by metallic emanations.[2] Becker, on the other hand, although he recognized that the hot springs met with in the Comstock lode must owe their abnormal heat to the effects of an expiring vulcanism, the focus of which he placed at between 2 and 4 miles depth, considered these waters (to which he attributed both the filling of the fissure and the propylitization of the andesites)[3] to be of meteoric origin, tentatively sug-

[1] Becker, *loc. cit.*, p. 12.

[2] Thus he wrote (*loc. cit., p.* 19): "We have in the elements evolved during the first two periods of solfataras, namely fluorine, chlorine and sulphur, all the conditions required for filling the Comstock fissure. . . ." Fluorine and chlorine are the most powerful volatilizers known, and form volatile combinations with almost every substance. Besides silicon, the metals have a great affinity with them. All those which occur in the Comstock vein could ascend in a gaseous state in combination with one or other of them. They must then be precipitated in the upper parts as metallic oxides or chlorides and in the native state. During the second period of solfataric action in which sulphur compounds were predominant "metallic oxides and chlorides were converted to sulphurets, and the presence of antimony caused the formation of sulph-antimoniurets, the principal one of which is stephanite."

[3] In the case of the Comstock andesites, this decomposition takes the form of propylitization, *i. e.*, a conversion of the ferro-magnesian silicates to chlorite, epidote, calcite, and pyrite, which Becker showed must have been due to the action of solutions containing alkaline sulphides or sulphuretted hydrogen.

gesting the Sierra Nevada (distant 12 miles from the Comstock) as their source.[1]

The United States not only is rich in great natural repositories of mineral wealth, but is fortunate in its economic geologists, whose keen observation and powers of deductive reasoning are admirably adapted to the study of their structure and genesis. That this is no idle saying, witness the splendid series of monographs and professional papers issued by the United States Geological Survey. I have referred to the work of Emmons and Becker; there are many others. To mention a few only: R. D. Irving, who wrote on the Copper-bearing Rocks of Lake Superior;[2] Lindgren, on the Copper Deposits of the Clifton-Morenci District, Arizona;[3] Weed, on the Geology and Ore-deposits of the Butte District, Montana;[4] Lindgren and Ransome, on the Geology and Gold Deposits of the Cripple Creek District, Colorado;[5] Van Hise and Leith, on the Iron-ore Deposits of Lake Superior.[6] Willet G. Miller's work in Canada on the Cobalt Silver district also deserves mention. His description of the characteristic features of the silver veins, right at the beginning of the mining operations of that camp, was of first importance; and his early recognition of the bearing of the Keewatin Series, which underlies the Cobalt conglomerates, on the life of the mines, exercised a salutary chastening influence on the exaggerated optimism of those responsible for the primary development of the field.

The laborious nature of the task of collecting and collating the material for such memoirs is well illustrated by the introductory remarks to Mr. Weed's Professional Paper.[7] The complexity of the geological structure of the Butte district necessitating very detailed observations,

[1] Becker, *loc. cit.*, p. 243.
[2] U. S. Geol. Surv. Monogr. No. 5, 1883.
[3] U. S. Geol. Surv. Prof. Paper No. 43, 1905.
[4] U. S. Geol. Surv. Prof. Paper No. 74, 1912.
[5] U. S. Geol. Surv. Prof. Paper No. 54, 1906.
[6] "The Geology of the Lake Superior Region," U. S. Geol. Surv. Monogr. No. 52, 1911.
[7] U. S. Geol. Surv. Prof. Paper No. 74, 1912.

"in every mine, maps of each level were transferred to note-books, and with these in hand the writer and his assistants carefully examined the drifts and cross-cuts and plotted on the maps the occurrence of each slip, vein, or fault, noting the dips, strikes and other important features. Stopes and raises were noted in the same way and sketches made of particular features of vein-structure and ore-occurrence."

Over a hundred miles of underground workings were examined in this manner.

Hitherto I have confined my remarks to lode-mining; but in the field of alluvial mining the economic geologist has also something to say. The fascinating task of tracing out, first by boring and then by drifting, the auriferous gravels of an ancient river system, deeply buried under a pile of more recent accumulations, which sometimes even include thick sheets of basaltic lava as in the Loddon valley at Ballarat, must have called for considerable geological acumen. I am unaware to whom the credit for the first discoveries of this nature in Australia and California is due, but I cannot forbear to mention Mr. Lindgren's remarkable reconstruction of the ancient (Tertiary) topography in the vicinity of Nevada City and Grass Valley in California. The map on which this work is recorded (the Tertiary configuration by heavy lines and the present contours by faint lines) clearly shows the ancient valleys with their tributary streams usually running at right-angles to the present drainage lines.[1]

The assistance rendered by geologists in prospecting for petroleum is well known to you. The earliest investigations of petroleum-fields, dating back to the middle of last century, led to the conclusion that great natural reservoirs of oil and gas tend to form along the axes of anticlinal folds or at the top of domes; it was also observed that the best conditions for oil-accumulation were those of gentle folding sufficient indeed to give a gradient along which the oil and gas could travel in the porous bed, but not intense enough to cause fissuring in the impermeable cover.[2]

[1] 17th Ann. Rep. U. S. Geol. Surv., 1896, Part II., pl. II.

[2] Sterry Hunt, "Geology of Canada," pp. 522–525, and contributions to the "Chemical and Geological History of Bitumens," *Amer. Journ. of Science*, Vol. XXXV., 1863, p. 157; Höfer, "Petroleum Industrie Nordamerikas," 1877, p. 81. Also ECON. GEOL., Vol. V., 1910, p. 492.

It must be conceded that the general correctness of this theory has been confirmed by the work of subsequent observers, and it will also be noted that the "anticlinal theory" is not quite as novel a conception as some of our friends would have us believe.

There can be no doubt that the search for these natural products is essentially a geological problem; and, to my mind, the fundamental qualifications for what is euphemistically termed "the oil-expert" are sound geology and common sense.

I shall refer later on to the important bearing on mining—especially on the mining of copper—of the researches of mining geologists on the origin of ore-deposits and notably in regard to the phenomenon of secondary enrichment.

Enough has been said to indicate the dependence of mining on geology; but that this dependence is not universally admitted is evidenced by the prejudice against both the mining geologist and the scientifically trained engineer occasionally found among mining employers, by whom they are sometimes unfavorably compared with the so-called "practical miner." Rule of thumb methods, however, in either mine-valuation or exploratory and development work can never command success; indeed the unschooled miner often enough realizes the value of geology and sets about acquiring such a working knowledge of its principles as will enable him to tackle the more prominent tectonic troubles met with in sinking or drifting.[1] But men of this stamp must be the exception rather than the rule, and it is clear that *ceteris paribus,* the trained man, who brings to mining problems a sound knowledge of the principles underlying their engineering and geological aspects, not only starts with a pronounced advantage, but is enabled to assimilate practical details with far greater rapidity and certainty when once his mining career has commenced.

The feeling, amounting even to suspicion with which geology is, in some quarters, regarded is, perhaps, attributable to the following causes: First there are the nonsensical reports on mines and mining prospects—such as most of us can recall—made by charlatans who by the use of an obscure geological phraseology

[1] Thus Spurr writes (*Eng. and Min. Journ.,* Vol. 75, 1903, p. 556): "Every miner is a mining geologist to the best of his ability."

seek to impose their trite conclusions on the credulity of their employers. Then there are the wearisome lucubrations of the irresponsible faddist who uses the columns of the local press to ventilate absurd geological theories. However, geology is not the only science to suffer from the ignoramus and the bore. A more serious disability perhaps lies in the employment in mining work of the academic geologist who has had no previous experience of mines and is unacquainted with mining conditions and economics. Imagine such a one—in his own province possibly a distinguished scientist—taken underground for the first time, groping his way in a murky atmosphere but dimly illumined by the miner's lamp or the glimmer of a candle, amid unfamiliar, and occasionally unpleasant, surroundings; imagine under such conditions his being asked to unravel the intricacies of a fault or prognosticate the downward extension of an ore-body. In fact the lavish natural indications, which at the surface attract the attention of the geologist, tend at first to elude him when he penetrates beneath it; since there the exposures are few in number, and such as they are, small; moreover, they are as a rule covered with dust, begrimed with soot, or buried in mud. Even to overcome initial difficulties, such as these, is not enough; to achieve a real success the work of the miner must be followed step by step, since in his progress he effaces the facts almost as soon as they are disclosed.

It must be abundantly clear that mining geology is a branch of the profession distinct from pure geology, and that proficiency in this specialized department cannot be attained without a proper underground training.

In the United States there is a growing tendency to differentiate the functions of the mining man; thus we find there an increasing use of the term "mining geologist" to designate a mining engineer strong on the geological side, or, what in practice amounts to the same thing, a geologist who has specialized in mining work. On the other hand, the term "mining engineer" is occasionally used in the restricted sense of a mechanical engineer who has specialized in mining machinery. Thus, Pro-

fessor Monroe, of Columbia University, in contributing to the discussion of a paper read before the Institution of Mining and Metallurgy,[1] said the mining engineer was called upon to design machinery for mining purposes and to superintend its construction and operation. He "should be able," he continued,

> "to test, among other things, the efficiency of boilers, steam and gas engines, air, hydraulic and other motors, pumps and compressors, electric lighting and power plants, telephone and telegraph systems, crushing, concentrating and amalgamating machinery and metallurgical plant, and to determine in each case whether the motive power, coal, gas, water, air, or electric current, is economically used, and the machines and mechanical devices are working to the best advantage. Or, if this is not the case, he should be able to diagnose the trouble and indicate the remedy, and determine the conditions of maximum efficiency and economy."

Surely in writing this Professor Monroe must have had in mind the application of mechanical engineering to mining, neglecting for the moment its exploratory side; for it is clear that mining consists of two distinct parts: (1) *the exploration and development of the ore-body;* and (2) *the extraction and bringing to the surface of the ore:* the first being essentially a problem in which geological principles are dominant; while in the second mechanical engineering plays the chief part.

Since the expression "mining geologist" appears to have taken a definite niche in the edifice of mining engineering it may be well to attempt a definition of his proper functions.

In the province of metal-mining, mining geology comprises the study of the ore-deposit, its lithological environment, its enrichments and impoverishments and their cause, and finally the faults and dykes that traverse it and their effect. As a result of such investigations the mining geologist is enabled to trace and define the ore-shoots; to predict, as definitely as the evidence will allow, their downward extension; to outline the scheme of development and method of mining best suited to their shape, size, dip and pitch[2] and having regard to any existing dyke or fault disturb-

[1] H. C. Jenkins, on the "Equipment of Laboratories for Advanced Teaching and Research in the Mineral Industries," *Trans. Inst. Min. and Met.*, Vol. XIII., 1904, p. 283.

[2] Using "dip" for the inclination of the vein walls to the horizontal in a

ance; to determine the amount and value of ore immediately or prospectively available; and from the nature of its mineral association to suggest the necessity, or otherwise, of eliminating the gangue by some form of ore-dressing or concentrating machinery; and, finally, to give a preliminary opinion, based on the mineral composition, as to the docility or refractoriness, as the case may be, of the ore in regard to metallurgical treatment.

It is evident that the examination of a supposed mining field, or of a lode or ore-body on which nothing but prospecting work has been done, is essentially the work of the mining geologist; and it may also be conceded that, provided he has served the requisite apprenticeship underground, understands the art of sampling, and can gauge with some approximation to accuracy the costs of mining and treatment, the inspection of a partially developed, or "young," mine may also be properly entrusted to the mining geologist.

In the case of a fully developed mine, in which the whole, or practically the whole, of the available ore is blocked-out for stoping, or at any rate is developed by drifts extending from end-line to end-line at the lowest levels permitted by the dip boundary of the property[1]—the requirements are somewhat different. Here what is wanted is not so much the drawing of inferences from the geological environment of the ore, but a correct appraisement of the net profits obtainable by its extraction with due regard to the economic conditions prevailing. In this case apart from the estimation of ore-reserves a consideration of the most suitable methods of extraction and treatment and questions of finance are of paramount importance. An actual apprenticeship in mine-management, supplemented by a long experience of mine-examination under the most varied conditions, are here the prime requisites for a successful evaluation.

Similar differences exist in regard to the management of mining properties. Prospecting and exploratory mining are essen-

plane at right angles to the strike and "pitch" for the inclination of the boundaries of the ore-shoots within the plane of the vein to the strike of the vein.

[1] Where the law of the apex obtains, there is no such limitation on the dip.

tially the work of the mining geologist. Even in the normal development of a mine, questions often arise that can not be solved without the aid of a sound knowledge of tectonic geology. It is true that on small mines the mine manager is often expected to possess the knowledge of the mining geologist, the mechanical engineer and the man of business. But big mines are, or should be, organized departmentally and are placed then under the supreme control of a man chosen chiefly for his executive ability and power of organization, irrespective of other attainments. The machinery is of course controlled by a mechanical engineer, the reduction works, by a metallurgist, the supply of ore, by an underground superintendent or mine-foreman; while the exploratory and development work is best superintended by the mining geologist. Surveying and sampling are natural adjuncts of the mining geologist's department, and indeed the mine-surveyor is often himself a competent geologist, recording on his plans the faults and dykes disclosed in development, and determining the quantitative effect of the disturbance and the loss or gain of ore thereby caused.

It must be evident that the point I wish to make is that the rôle of geology in mining is more important than is generally conceded and that a recognition of this involves either an extended geological training for the mining engineer or a relegation of a portion of his functions to the mining geologist who has been trained in underground work. After all whether a man is called a mining engineer or a mining geologist is of little moment;[1] the important point is, that the student who purposes to take up mining work as a profession should receive the best possible training for that end, and in this, I contend, geology must have a prominent place. The mining employer, for his part, should in all cases have a clear conception of what is essential for the proper development of his property and should be able to choose a man whose special studies have fitted him for the particular work involved.

[1] Thus Lindgren writes (*Eng. and Min. Journ.*, Vol. 75, 1903): "I draw no line between the mining engineer and the mining geologist, though in their highest development each represents a technical or scientific specialization of the ordinary type of the profession."

If the mining employer requires guidance in this choice—that is the function of the consulting engineer.

I now pass on to ore-genesis—a more theoretical branch of my subject; but one nevertheless of the greatest importance to the engineer engaged in mine examination, for it is evident that every forecast of the continuity of an ore-body beyond the limits of the ore in sight, must, if it is not to be entirely empirical, rest on some hypothesis as to origin. This field of enquiry has, since the beginning of this, and during the latter half, of the past century, riveted the attention of the best mining geologists in all parts of the world. Indeed so much has been written in recent years on the subject, that a short account of the development of modern views will perhaps be welcomed.

In a comparatively small interval of time, our knowledge has advanced by leaps and bounds,[1] and many important principles governing ore-deposition have been firmly established.

It was, however, preceded by a long period which, although fertile in suggestion and hypothesis, was not one of real progress because contrary to the Baconian principle[2] the theories advanced were not founded on ascertained facts. Before dealing with more modern theories I propose to pass in brief review the more suggestive of these earlier hypotheses.

Prior to the sixteenth century the metallic contents of ore-veins were supposed to have been determined by their orientation in regard to the planets; and Agricola[3] (1494–1555) was the

[1] Owing chiefly to the introduction of the microscope for the examination of thin sections of rocks and vein-fillings in transmitted polarised light; or where the minerals are opaque of polished slices by reflected light. Cp. W. Campbell: "The Microscopic Examination of Opaque Minerals," Econ. Geol., Vol. I., 1896, p. 751.

[2] "Non fingendum aut excogitandum sed inveniendum, quid natura faciat aut ferat."

[3] George Agricola, "De Ortu et Causis Subterraneorum," Basel, 1546, Lib. V., Chap. VII. Cf. also footnote on pages 46 and 51 of Mr. and Mrs. Hoovers' translation of "De Re Metallica." Prior to the chemical conceptions based on the atomic theory, writers on vein-formation expressed themselves in a language which, from our present point of view, seems archaic and abstruse. Their use of such expressions as, "juices," "humours," "menstrua," "exhalations," "fermentations" and "transmutations" recalls the language of the alchemists. I have used a more modern phraseology in the above and following notes.

first to formulate a reasonable genetic theory. Reduced to its simplest terms, Agricola's view was that ore-channels (*canales*), formed by erosion, had been filled by metallic minerals deposited from solution. These solutions, or juices (*succi*) as Agricola terms them, were waters of meteoric origin, which, under the influence of heat, had taken mineral matter into solution.

From the time of Agricola to the end of the eighteenth century the mines of Saxony produced nearly all the writers on vein-formation. Such were Rösler, Becher, Henckel, Hoffmann, Zimmermann, von Oppel, von Charpentier and von Treba.

Becher[1] and Henckel,[2] who wrote in the beginning of the eighteenth century, supposed the metallic constituents of veins to have been produced by the action on preëxisting stony and earthy matters of subterranean vapors arising from certain processes of "fermentation" in the bowels of the earth.

In 1749 Zimmermann[3] put forward a hypothesis which clearly had in it the germ of the modern theory of metasomatism. He ascribed the origin of veins to a transformation of the rocks into metallic minerals and their accompanying vein-stones, along certain directions now marked by the course of the veins, the solvents that effected this alteration finding a path through innumerable small rents and other openings in the rocks. But Zimmermann applied his theory indiscriminately to explain the origin of all veins, including those that, by common agreement, are now considered to have been formed by the filling of fissures without replacement. Von Treba,[4] in supporting Zimmermann's view, insisted particularly on the far-reaching changes effected in rocks by circulating waters, especially when aided by heat. He wrote in 1785:

"I am persuaded that there is constantly going on in our mountains a variety of transformations, compositions and decompositions, which not only take place at present, but will continue to the end of time."

[1] Jo. Joachim Becher, "Physica subterranea," Leipzig, 1703.

[2] Joh. Fr. Henckel, "Pyritologia," Leipzig, 1725.

[3] Carl Fred Zimmermann, "Obersächsische Bergakademie," Dresden und Leipzig, 1749.

[4] "Erfahrungen vom Innern der Gebirge nach Beobachtungen gesammelt und herausgegeben," von Friedrich Wilhelm Heinrich von Treba; Dessau und Leipzig, 1785.

According to Gerhard,[1] who wrote in 1781, waters circulating through the rocks adjacent to a vein become charged with certain of the metallic and earthy substances contained in them. Passing through the crevices and interstices of the rocks to the larger rents and fractures, they deposit their mineral burden in cavities which, when filled, become veins. It will be seen that Gerhard's hypothesis must be regarded as a precursor of the more modern *theory of lateral secretion.*

To von Oppel[2] belongs the credit of having shown that mineral veins were largely the filling of fault-fissures, a principle which, up to that time, does not appear to have been clearly recognized.

At the end of the eighteenth century, the mining world was dominated in all matters relating to ore-genesis by the famous Freiberg professor, Abraham Gottlieb Werner,[3] who insisted that all veins including those that we now term "intrusive dykes" had resulted from the filling of contraction-fissures open above and connected with the primæval universal ocean, which according to the Wernerian doctrine covered the globe and contained in solution all the necessary materials for the formation of its crust. These waters, descending into the fissures from above, deposited the vein-minerals by chemical precipitation.

This Neptunist view was in the beginning of the nineteenth century attacked and finally overcome by Hutton[4] and his Pluto-

[1] Carl Abraham Gerhard, "Versuch einer Geschichte des Mineral-Reiches," Berlin, 1781.

[2] "Essay on the Working of Mines," c. 1749, paragraphs 27–42.

[3] Werner, "Neue Theorie von der Entstehung der Gänge mit Anwendung auf den Bergbau, besonders den freibergischen," Freiberg, 1791. See also translation by Anderson, Edinburgh, 1809. The following paragraphs are noteworthy; Chap. III., § 28 (p. 51): "Alle wahre Gänge sind wirkliche, anfänglich (nothwendigweise) offen gewesene, und nachher fast blos *von oben herein ausgefülte Spalten.*" *Ibid.*, 30 (p. 52): "Der nämliche nasse Niederschlag, welcher die Lager und Schichten der Gebirgsmassen, und unter solchen auch die vielen erzführenden erzeugte, bildete auch die Gangmassen." *Ibid.*, Chap. IV., § 49 (p. 79): "Zu dergleichen Ausfüllungen sind alle Granit, Porphir, Basalt, Grünstein, und dergleichen Gänge zu zählen. Denn, wenn sich diese Gesteine als Gebirgsmassen aus nassen Niederschlage erzeugten, so lässt sich, auch dann wenn sie als Gangmassen vorkommen, kein anderer Ursprung denken."

[4] Hutton, "Theory of the Earth," Edinburgh, 1795, and Playfair, "Illustrations of the Huttonian Theory of the Earth," Edinburgh, 1802.

nist or Vulcanist school. Unfortunately, however, the Plutonists went to the other extreme, and would not allow even ore-veins to have any other than an igneous origin: "the materials," wrote Playfair, "which fill the mineral veins were melted by heat and forcibly injected into the clefts and fissures of the strata."[1] But Hutton's broad generalization, even with the important modifications of Élie de Beaumont,[2] Daubrée[3] and Durocher[4] to the effect that many of the metallic ores had been deposited from vapors and solutions emanating from cooling igneous magmas, was soon discarded in favor of deposition from waters of meteoric origin;[5] and an animated discussion was maintained for half a century on the respective merits of the *descensionist, ascensionist* and *lateral secretionist* theories: or in other words, whether the mineral burden of the circulating waters instrumental in vein-formation, was derived from superficial rocks, from deep-seated sources, or from the wall-rocks of the veins themselves.

The chief supporters of the modified form of the ascension theory here alluded to, which must of course be distinguished from De Beaumont's ascension by emanation, were Stelzner[6] and Posepny.[7] They argued that the ground-water (originating by precipitation from the atmosphere) descends by capillarity through

[1] Playfair, "Illustrations of the Huttonian Theory," 1802, p. 601.

[2] Élie de Beaumont, "Sur les émanations volcaniques et métallifères," *Bull. de la Soc. Géol. de France,* 1847, p. 1249.

[3] A. Daubrée, "Du gisement, de la composition et de l'origine des amas de minerai d'étain," *Ann. des Mines,* Vol. XX., 3d series, 1841, p. 65.

[4] Durocher, "Recherches sur les depôts métallifères et sur leur mode de formation," *Comptes rendus,* Vol. XXVIII., 1849, p. 607.

[5] Thus Sandberger wrote in 1882: "Die Modification der Ascensions-Theorie, welche nicht Absatz von Erzen durch aufsteigende Mineralquellen, sondern durch Metalldämpfe annimt, wird vielleicht noch von einem oder dem anderen Geologen angenommen, aber von der überwiegenden Majorität verworfen" ("Untersuchungen über Erzgänge," I., 1882, p. 17).

[6] Stelzner, "Beiträge zur Entstehung der Freiberger Bleierzund der erzgebirgischen Zinnerz-gänge," *Zeits. f. prak. Geol.,* Vol. 4, 1896, p. 377.

[7] Posepny, Über die Bewegungsrichtung der unterirdischcirculirenden Flüssigkeiten," Rep. Geol. Congress, Berlin, 1885, p. 71. See also "The Genesis of Ore-Deposits," *Trans. of the American Inst. of Min. Engineers,* Vol. XXIII., 1893, p. 197.

the interstices of the rocks to deep-seated regions and thus acquires a high temperature and pressure and, consequently, a vastly increased solvent power, whereby in its passage through the rocks it is enabled to take up certain of the mineral substances there disseminated in a minute form. At a certain depth the water moves laterally towards open conduits, on reaching which it ascends towards the surface, depositing its mineral burden in proportion to the decrease of temperature and pressure.

We have seen that the theory of lateral secretion, or the derivation of the mineral contents of veins by an aqueous leaching of the country rock, was advanced in a crude form as early as 1781 by Gerhard; but it remained a mere hypothesis without the support of ascertained facts until the middle of the 19th century, when the chemical work of Bishof,[1] Forchhammer,[2] and Sandberger,[3] definitely established two important facts in support of the theory, namely: (1) that the gangue of ore-veins frequently varies in correspondence with the wall-rock; and (2) that the heavy metals occur in minute traces in certain of the igneous and sedimentary rocks constituting the "country" of ore-veins.

Sandberger's researches were specially directed to prove that the heavy metals (gold, silver, copper, lead, etc) are contained in the common ferro-magnesian silicates (namely the micas, hornblendes and augites) of the igneous rocks; and having satisfied himself on this point he was led to extend his investigations to the sedimentary rocks, with the result that small quantities of the heavy metals were found in the sediments of all ages, and especially in the slates of the older systems. Whether, however, they are there present as constituents of sporadic fragments of ferro-magnesian silicates derived from igneous rocks, or as sulphides that have been subsequently introduced during the secondary mineralization connected with ore-deposition, was not satisfactorily settled by Sandberger's researches.[4] The more recent

[1] Bishof, "Physical and Chemical Geology," 1846–1847.

[2] Forchhammer, *Poggendorfer Annalen*, Vol. XCV., 1855, p. 60.

[3] Sandberger, "Untersuchungen über Erzgänge," I., 1862, II., 1885. Wiesbaden.

[4] A commission consisting of V. Foullon, C. Mann, A. Patera, Posepny, and V. Sandberger, appointed in 1884 to examine the Pribram veins with the object of ascertaining whether they owed their silver-lead content to lateral

work of Don, carried out on a great variety of material, tends to show that the ferro-magnesian silicates do not carry gold or silver in amounts determinable by chemical analysis; where the rocks examined by him were found to contain these metals, they were present as a constituent of sulphides such as iron pyrites, pyrrhotite, mispickel, chalcopyrite and galena, which in most cases are secondary introductions.[1]

But long before this, the inapplicability of lateral secretion, as Sandberger conceived it,[2] soon became apparent; and the theory became the subject of vigorous attack on the part of Stelzner[3] and Posepny.[4]

Lateral secretion in a much more extended sense, and in combination with the ascension theory, is advocated by Van Hise.[5] This modification of the theory will be referred to in a later part of my address.

In recent years there has been a partial reaction to igneous views. Thus certain classes of ore-deposits are now held to have been formed by a *differentiation of igneous magmas* prior to

secretion, reported that small quantities of silver, lead and copper were found both in the eruptive and in the sediments forming the country rock of the veins. (The average tenor in silver was .00043 per cent. in the sediments and .00045 per cent. in the eruptives.) But whether the metals occurred as sulphides or as silicates was not decided. Moreover, similar quantities of lead and silver were found in samples of the rocks taken from districts in which the veins were barren of ores of these metals. (See *Neues Jahrbuch für Min.*, etc., 1888, II., p. 56.)

[1] J. R. Don, "The Genesis of Certain Auriferous Lodes," *Trans. Amer. Inst. of Min. Eng.*, Vol. XXVII., p. 564.

[2] Sandberger's *ipssissima verba* in defining lateral secretion are: "eine Auslaugung des die Spalten begränzenden Nebengesteins durch Sickerwässer, welche dasselbe durchdrungen haben und die gelösten Stoffe als Erze und Gangarten in den Spalten desgleichen oder ausnahmsweise auch in solchen des nächsten Nachbargesteins wieder absetzen" ("Untersuchungen über Erzgänge," Wiesbaden, 1882, p. 17).

[3] A. W. Stelzner, *Ueues Jahrbuch für Min.*, 1883, I., p. 236; *ibid.*, 1886, II., p. 220; *ibid.*, 1888, II., p. 56.

[4] Posepny, "Untersuchungen von Nebengesteinen der Pribramergänge mit Rücksicht auf die Lateral-secretions theorie des Professors Dr. F. v. Sandberger," *B. u. H. Jahrb. der k. k. Bergakademie*, Vol. XXXV., 1887, p. 299.

[5] Van Hise, "Some Principles Controlling the Deposition of Ores," *Trans. A. Inst. Min. Eng.*, Vol. 30, 1902, p. 339.

consolidation.[1] Such for instance is the origin ascribed to certain titaniferous iron-ores in basic eruptives (*e. g.,* Ekersund-Soggendal in Norway, and Taberg and Routivara in Sweden); chromite in peridotites, nickeliferous pyrrhotite in norite (*e. g.,* Sudbury in Ontario and Lancaster Gap, Pennsylvania); and primary platinum in ultrabasic rocks (*e. g.,* Nischne Tagilsk and Mount Solovief in the Urals). Similarly pegmatites and even some quartz-veins are considered to have originated by the consolidation of the aqueo-siliceous residuum of a slowly cooling granite magma.[2]

But more important in its application to ore-deposition than *magmatic differentiation* is the theory which Vogt[3] has founded on the metalliferous emanation hypothesis, by which Élie de Beaumont and Daubrée[4] sought to explain the origin of tin-ore deposits. According to the *pneumatolytic*[5] theory, certain *agents minéralisateurs* such as fluorine, chlorine, sulphur, phosphorus, silicon and boron have the property of forming with the metals volatile compounds, which escape from the granite-magma as gases with low critical temperatures (the *aura granitica* of Élie de Beaumont). These compounds ascend through already formed fissures in the overlying rocks, or force their own passage by attacking the minerals that compose them. In this manner for instance cassiterite,[6] wolfram, tourmaline, fluor-spar, topaz,

[1] See Vogt's papers in the *Zeitschrift für practische Geologie,* 1893, 1894, 1895, 1898, and 1900. Also *Trans. Amer. Inst. of Min. Eng.,* Vol. XXXI., 1901, p. 125.

[2] Brögger, *Zeitsch. f. Kryst. u. Min.,* Vol. XVI., 1890, and Spurr, 18th Ann. Rep. U. S. Geol. Surv., 1897, Part III., p. 312. Hussak, *Zeitsch. f. prakt. Geol.,* 1898, p. 345. The view expressed above originated with Lehmann, "Die Entstehung der altkrystallinischen Schiefergesteine," Bonn, 1884, p. 55.

[3] Vogt, *Zeitsch. f. prak. Geologie,* 1894, p. 458, 1895, Nos. 4, 9, 11 and 12.

[4] See *loca citata* on p. 221.

[5] *Pneumatolysis* is a term introduced by Bunsen—"unter dieser Klasse von Bildungen sind die manchfaltigen Produkte zusammengefasst, welche aus der Einwirkung der vulcanische Gase und Dämpfe auf Gesteine hervorgehen": über die prozesse der vulkanischen Gesteins-Bildungen Islands, *Poggend. Annal.,* 1851, Vol. LXXXIII., 1851, p. 197. Abstract in *Neues Jahrb.,* 1851, p. 863.

[6] In support of this Daubrée synthetically produced cassiterite by sublima-

beryl, axinite, datolite, apatite, etc., are deposited either in the granite itself, or in the sediments comprised within its metamorphic aureole.[1]

Closely connected with pneumatolysis is the rôle ascribed in ore-deposition to the so-called *magmatic waters,* a term that has come into use for water not of atmospheric origin but dissolved or occluded in some way in molten magmas, from which it separates by liquation and distillation on the fall of temperature and pressure. In it are concentrated the substances that (at the existing temperature) are more soluble in water than in the silicate magma.[2]

Suess,[3] in an address on the Karlsbad springs delivered in 1902, drew attention to the connection existing between thermal springs, vulcanicity, and ore-deposition. He applied the term *hypogene* or *juvenile* to thermal springs (like those of Karlsbad) which, originating in the depths of the earth's crust, bring water to the surface for the first time. Such hot springs are in fact the last survivors of vulcanicity, being the relics of a late stage of fumarole activity. Their mineral content comprises readily soluble compounds of the alkalies and alkaline earths, together

tion according to the reaction

$$SnCl_4 + 2H_2O = SnO_2 + 4HCl,$$

Ann. des Mines, Vol. XVI., 4th series, 1849.

[1] Apatite deposits are of similar origin, but with this difference that they are genetically connected with a gabbro- instead of a granite-magma.

[2] See Lehmann, *loc. cit.,* pp. 24–58; also Reyer, "Theoretische Geologie," 1888, p. 192. Reyer writes: "Die starren Teile (des Magmas) sind mit Flüssigkeiten (Wasser) durchtränkt und diese sind mit Gasen gesättigt," and, p. 193: Gase sind "in Innern der Erde seit jeher gefesselt."

[3] E. Suess, "Ueber heisse Quellen," *Verh. Ges. deutsch. Naturf. u. Aerzte,* Karlsbad, 1902. See also *Naturwissenschaftliche Rundschau,* 1902, p. 588 and an abstract in the *Geogr. Journ.,* Vol. XX., 1902, p. 517. Compare also "Das Antlitz der Erde," Vol. III., 2, 1909, p. 630, or in Sollas' translation, "The Face of the Earth," Vol. IV., 548. A. Gautier's papers have a similar import: "La genèse des eaux thermales et ses rapports avec le volcanisme," *Annales des Mines,* 10th ser., Vol. IX., 1906, p. 316 (abstract in Econ. Geol., Vol. I, 1906, p. 688) and *Comptes Rendus,* Vol. CXXXII., 1901, p. 740. See also Bunsen, "Über vulkanische Exhalationen," *Neues Jahrb.,* 1852, p. 501. [See also A. L. Day, Carnegie Institution.]

with, and partly in combination with, sulphur, chlorine and carbon dioxide: the less soluble metallic compounds having already been deposited as ores at lower depths in the earth's crust. According to Suess the after-products of eruption vary with the temperature: in the earlier (pneumatolytic) *phases of emanation,* the gases are dry and their deposits (such as tin-ore and its accompanying boron, fluorine, tungsten, and uranium minerals) are the products of sublimation. At a later period, strongly alkaline magmatic waters are given off, and to these are attributable the *sulphide* and *arsenide phases* of vein-formation, *e. g.,* the deposition of iron-pyrites, chalcopyrite, primary bornite and chalcocite, enargite, galena, blende, etc.

A notable illustration of the formation of ores by deposition from magmatic waters has been given by Sales[1] in a recent paper on the ore-deposits of Butte, Montana, which, as is well known, consist of veins of copper and silver ores, associated with quartz-porphyry dykes traversing granite. These dykes represent a late differentiation phase of the parent granite magma. Their injection along the earliest fractures in the granite stimulated the upward movements of the vein-forming waters, which are believed by Sales to be a product of the same fluid magma as gave rise to the dykes. The high temperature of the waters and their consequent vigorous chemical activity, is indicated by the intensely altered condition of the wall-rocks. It is concluded that the primary constituents of the magmatic waters were fluorine, sulphur, arsenic, antimony, copper, zinc, manganese, lead, silver, tungsten and barium, since most of these metals are very minor constituents of the normal granite and some have not even been detected by chemical analysis of fresh rock. Probably the sulphur was originally in the form of hydrogen sulphide. The composition of the granite "country" under the solfataric action of the waters, liberated sodium and calcium, which were carried away by the ascending waters in the form of soluble alkaline sulphides. In a similar manner iron and silica were taken up,

[1] Sales, "Ore-deposits at Butte, Mont.," *Trans. Amer. Inst. of Mining Engineers,* Vol. XLVI.

to be deposited later as pyrites and quartz; and these minerals constitute the principal gangue of the veins.

The important primary minerals in the copper veins are chalcocite, enargite, bornite and chalcopyrite; while galena, blende and rhodochrosite are more characteristic of the silver veins. The copper mineralization appears to have taken place under high temperature conditions, which, as the solutions migrated towards the peripheral fractures now represented by the manganese-silver veins, were succeeded by those of lower temperature and greater alkalinity.

Mr. Sales's conclusions in support of the primary origin of the chalcocite, are based on the following facts: The sooty chalcocite, the secondary origin of which is indisputable, is confined to a zone extending from the bottom of the oxidized zone to depths varying from 100 to 1,200 feet. It is not found to be succeeded by lean cupriferous pyrites, as was anticipated, but by massive chalcocite which, in admixture with bornite and enargite, extends to the bottom levels of the mines at depths of over 3,000 feet, and, in marked contrast to the sooty chalcocite, bears no relation to the surface topography. The fact that these bodies are cut by old faults also tends to show that they are of considerable geological antiquity and not genetically related to the superficial circulation of the ground water.

Special attention is directed by Sales to the Mountain Chief ore-shoot of the Jessie vein, which extends to the surface. A small oxidized zone containing a rich ore composed of cuprite and iron-oxides, is succeeded by a pyritic zone in which the metallic minerals are pyrites, chalcopyrite and blende. The upper part of this pyritic zone shows secondary enrichment, the primary chalcopyrite and pyrites being coated with secondary sooty chalcocite. At about 500 feet from the surface the chalcopyrite zone is replaced by an ore consisting of chalcocite, bornite, enargite and pyrites with chalcopyrite in complete subordination. Consequently it would appear that chalcopyrite, being a lower temperature mineral than chalcocite or enargite, its development was restricted to the higher parts of the vein. In this connec-

tion it is also noted that both enargite and chalcocite often show a tendency to alter to bornite and to chalcopyrite, such alterations being attributable to changes in the physical conditions of the ascending magmatic solutions.

I have dwelt at some length on the conditions of mineralization described by Sales as prevailing during the formation of the Butte ores, because the fact that a large proportion of the chalcocite of the copper veins of that district is now shown to be of primary origin, and not a product of secondary sulphide enrichment[1]—as was previously supposed—is of vital importance, since it must affect engineers' estimates as to the downward continuity of rich ore-shoots in copper mines.

It ought perhaps here to be stated that the theory of ore-deposition by waters of magmatic origin is not universally accepted. An important school, of which we may take Van Hise as the representative, still regards meteoric waters as the main factor of ore-deposition. Van Hise's view may be briefly summarized thus:[2] The meteoric waters after penetrating the surface, are widely scattered through the rocks in innumerable small openings as they travel downward to great depths in the earth's crust. With steadily increasing temperature and pressure they take up mineral matter. The downward movement ultimately develops a lateral component, by which the waters are carried to the larger openings. During this process also, the waters continue to take material into solution. In the larger openings the waters ascend, with decreasing temperature and pressure, and there the ores are deposited.

It will be seen that this view is a combination of the ascension and the lateral secretion theories, and presupposes the existence

[1] A. F. Rogers (ECON. GEOL., Vol. VIII., 1913, p. 781) has recently brought forward evidence based on microscope work, tending to show that at Butte the chalcocite is of three kinds and origins, namely (1) primary chalcocite formed by ascending solutions, (2) secondary chalcocite formed of ascending solutions, (3) secondary chalcocite formed by descending solutions.

[2] Van Hise, "Some Principles Controlling the Deposition of Ores," *Trans. Amer. Inst. of Mining Eng.* See also Le Conte, "The genesis of Metalliferous Veins," *Amer. Journ. of Science,* Vol. XXVI., 1883, p. 1, and Becker, "The Geology of the Comstock Lode," U. S. Geol. Survey Monogr. III., 1882.

of a continuous sheet of water in circulation between the ground-water level and the lower limit of the "zone of fracture," no circulation being admittedly possible in the underlying "zone of flowage." The weak point in Van Hise's assumption of a "sea of underground water" lies in the fact that deep mines are usually found to be dry, the drainage being confined to the upper levels. This, for instance, is the experience in the copper-mines of Lake Superior, in the gold-mines of the Rand, and in those of Bendigo.[1] Van Hise,[2] in reply to this criticism, attributes this dry zone to the closing of the passages by cementation; but the restriction of the ground-water circulation is equally fatal to the meteoric derivation of deep-seated thermal springs and other phenomena connected with vulcanicity.

But although, as we have seen, waters of meteoric origin have been displaced from their pride of place as agents of deposition for what we must now term the primary sulphide ores, they are undoubtedly the formative agents for a considerable number of ore-deposits, including the products of oxidation, chlorination and reduction above the permanent water level, and the secondary enriched ores usually found immediately below the junction of the zone of oxidation with the zone of primary sulphides.[3] So important are the functions of the vadose waters (to use Posepny's term for the shallow water circulation) in dissolving and redepositing at a lower level the ores of copper in a con-

[1] See Rickard, *Trans. Amer. Inst. Min. Eng.*, Vol. XXX., p. 377, and Kemp, "Igneous Rocks and Circulating Waters as Factors in Ore Deposition," *ibid.*, Vol. XXXIII., p. 699.

[2] Van Hise, "Some Principles Controlling the Deposition of Ores," *Trans. Amer. Inst. of Min. Eng.*, Vol. XXVI., p. 292, and "A Treatise on Metamorphism," Chap. 12, U. S. Geol. Surv., Ming. 47, 1904.

[3] See on this subject Penrose, "The Superficial Alterations of Ore-deposits," *Journ. of Geol.*, 1894, p. 306; Douglas, "The Copper Queen Mine, Arizona," *Trans. Amer. Inst. Min. Eng.*, Vol. XXIV., 1900, p. 532; Emmons, "Economic Geology of the Butte District," Geol. Atlas of the U. S., Butte special folio, 1897, and *Trans. Amer. Inst. Min. Eng.*, Vol. XXXI., 1901, p. 169; Emmons, "Geology and Mining Industry of Leadville, Colorado," U. S. Geol. Surv. Min. XII., 1896; Emmons, "The Secondary Enrichment of Ore-deposits," *Trans. Amer. Inst. Min. Eng.*, Vol. XXX, 1900, p. 177. Weed, "Enrichment of Mineral Veins by Later Metallic Sulphides," *Bull. Geol. Soc. Amer.*, Vol. XI., 1900, p. 179.

centrated form, that it has been confidently stated that the bulk of the copper production of the world, not alone in the past, but also at the present time, is drawn from the zone of secondary enrichment.[1] This view will perhaps appear exaggerated in the light of the results obtained by Sales at Butte; but for the majority of the great copper deposits of the world it may still pass unchallenged.

In the same way vast deposits of high grade iron-ore have been formed as the result of secondary enrichment, but under entirely different conditions to those that determined copper-ore enrichments. Thus the hæmatite-ores of Lake Superior are believed by Van Hise to have been derived by the oxidizing and concentrating action of vadose waters, from a low-grade cherty iron carbonate originally deposited under water as a chemical sediment; and he draws the important conclusion that "the ore-bodies cannot be expected to extend beyond the depth to which the descending waters may bear oxygen and precipitate iron-oxide." He has "no doubt that vastly more high-grade iron-ore will be taken out in the Lake Superior region above the 1,000 foot level than below it." If this be true, the iron-ores of that district, with more than 60 per cent. of metallic iron, are not inexhaustible.[2]

The enrichment of gold ores also takes place in the zone of oxidation;[3] but in their case the action of the vadose waters is to abstract the more soluble and less valuable metals, leaving behind a smaller quantity but a relatively richer material: in other words, a diminution of the specific gravity of the whole material raises the gold tenor. Furthermore there is an increase in the fineness of the gold, due to the removal of a portion of the silver

[1] Knox, *Trans. Inst. Min. and Metallurgy*, Vol. XVIII., 1909, p. 290.

[2] Van Hise, "Iron-ore Deposits of the Lake Superior Region," U. S. Geol. Surv., 21st Ann. Rep., 1900, Part III., p. 305, and Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," U. S. Geol. Surv., Mining, 52, 1911, p. 568. See also "Genesis of Lake Superior Ores," ECON. GEOL., Vol. I., 1905, p. 47.

[3] Secondary enrichment in the zone of oxidation forms the subject of a communication by De Launay, "Rôle des phénomènes et de remise en mouvement dans la formation des gites métallifères," *Ann. des Mines*, 1897, p. 147.

with which it is alloyed.[1] The Mount Morgan mine in Queensland is a good instance of a gold ore enrichment brought about by the vadose circulation: here the oxidation of a pyritic copper lode with subordinate gold has, by the removal of the sulphides of iron and copper, led to the formation of an upper zone of cellular quartz, in which the increased ratio of gold to vein-stuff was the *vera causa* of the richness of one of the premier gold-mines of the world. But as with increasing depth the mine-workings are extended below the oxidation-zone the copper production is becoming more important than the gold yield.[2]

The Witwatersrand Banket is another example. In this case the primary ore is auriferous iron-pyrites disseminated in a quartz-conglomerate on which intense silicification during cementation has impressed the character of a quartz vein. The removal of the pyrites from the zone of oxidation, which extends to 200–300 feet below the surface, left an enriched free-milling ore that gave marvellous returns on the amalgamation plates of the first Rand mills. Since the exhaustion of this high-grade free-milling ore early in the history of the Rand the mines have been worked in low-grade unoxidized pyritic ore; and this has shown a gradual but steady impoverishment with increasing depth,[3]—a fact which supports the view that the gold of this deposit was precipitated by ascending thermal waters in proportion to their loss of temperature and pressure.

One of the most remarkable advances in the science of ore-genesis during the period under review, is the recognition of the important rôle played by metasomatism in the formation of

[1] J. R. Don, "The Genesis of Certain Auriferous Lodes," *Trans. Amer. Inst. Min. Eng.*, Vol. XXVII, p. 564.

[2] The Mount Morgan Gold-mining Company has since the formation of the company in 1886 down to May 31, 1913, produced gold and copper to the value of 19 million pounds sterling, of which about 16.4 millions is from gold and 2.6 millions from copper. During the year ended May 31, 1913, the company produced gold and copper to the value of £1,130,387, of which about £500,000 was from gold and £600,000 from copper (Report for year ended May 31, 1913).

[3] See H. H. Webb in annual report for 1913 of the Consolidated Gold Fields of South Africa; and Hatch, "Impoverishment with Depth on the Rand," *Mining Magazine*, Vol. IX., 1913, p. 450.

ore-bodies. The fact that the rocks adjacent to vein-fillings often contain small quantities of metallic ores similar to those composing the veins themselves, or are altered for some distance away from them, was observed at an early date; but its significance was very differently interpreted. The lateral secretionists pointed on the one hand to ore-disseminations in the wall-rocks as indicating the source of the vein-filling and on the other, to their alteration as a concomitant of the leaching that collected the filling material. But the ascensionists, whether belonging to the school of Élie de Beaumont and Durocher or to that of Stelzner and Posepny, recognized that the solutions from which the materials of the lode were precipitated, whether gaseous or liquid, also penetrated the walls and there caused certain deposits in the rock itself,—metallic ores taking the place of some other mineral dissolved, as for example when cassiterite forms pseudomorphs after felspar in the granite country of tin-veins.[1] Much evidence favoring the latter view has since been accumulated. Thus Posepny[2] described in 1873 the replacement of carbonate of calcium by carbonate of zinc in the Raibl deposits; and Pumpelly[3] in the same year attributed the origin of the native copper of the famous Michigan deposits to metasomatic processes. In 1881, Emmons[4] showed that the Leadville silver-lead deposits had been formed by the replacement of limestone by galena, blende and pyrites, an alteration which, although chemically complete, left untouched the granular texture, joints and other structural features of the original limestone. He pointed out that the resemblance of the altered rock to limestone was so perfect, that, when the faces of the drifts were covered with dust, the observer was often completely deceived until the breaking of a fresh fragment

[1] Daubrée, "Sur le gisement, la constitution et l'origine des amas de minerai d'étain," *Ann. des Mines*, 1841, p. 110.

[2] Posepny, "Die Blei und Zalmei Erzlagerstätter von Raibl in Kärnten," *Jahrb. d. K. K. Geol. Reichsanstalt*, Vol. XXIII., 1873, p. 317.

[3] Pumpelly, "The Metasomatic Development of the Copper-bearing Rocks of Lake Superior."

[4] Emmons, Ann. U. S. Geol. Surv., 1881, p. 201. This was an abstract of Emmons' Report on the Geology and Mining Industry of Leadville, Colorado, published as Monograph 12 of the U. S. Geol. Survey in 1886.

with the hammer revealed the metallic gleam of galena beneath. In a later paper[1] he showed that many so-called fissure-veins were not true cavity-fillings, but owed their origin to the metasomatic replacement of the rock material by substances brought in by solutions circulating along fault-fissures, through crush-zones or in sheeted zones. In such cases a vein may be formed by the replacement of the material enclosed between adjacent parallel fractures, true cavity-filling being of a restricted character. Owing to the difference in character between the replaced sheets of country rock and the filling of the fissures that divide them, deposits formed in this way sometimes possess a banded structure, which however is distinguishable from the normal "crustification" of vein-fillings. The whole subject has been admirably reviewed by Lindgren and by J. D. Irving in their well-known papers, in which will be found many illustrations of the potency of metasomatic processes in vein-formation.[2]

An important case of metasomatic replacement recognized in recent years are the great lenses of cupriferous iron pyrites worked for copper in the Huelva District of Spain (Rio Tinto, etc.), in the Ural Mountains, in the Western states of the United States, and in Tasmania (Mt. Lyell). Thus Finlayson[3] has shown that the primary pyritic ores of the Huelva deposits are replacements of crushed rock and are due to the action of magmatic waters on shear-zones along planes of faulting and thrusting in the neighborhood of porphyry intrusions in Culm slates; although their economic importance is mainly due to sulphide enrichment by meteoric waters. Similarly Nikitin[4] has described the pyritic lenses of the Verk-Issetsk Estates in the Urals as

[1] Emmons, "The Genesis of Certain Ore-deposits," *Trans. Amer. Inst. Min. Eng.*, Vol. XV., 1886, p. 125, and "The Structural Relations of Ore-deposits," *ibid.*, Vol. XVI., 1888, p. 804.

[2] Lindgren, "Metasomatic Processes in Fissure Veins," *Trans. Amer. Inst. Min. Eng.*, Vol. XXX., 1900, p. 578, and "The Nature of Replacement," ECONOMIC GEOLOGY, Vol. VII., 1912, p. 512. See also J. D. Irving, "Replacement Ore-bodies and Criteria for their Recognition," ECONOMIC GEOLOGY, Vol. VI., 1911, pp. 527 and 619.

[3] Finlayson, ECON. GEOL., Vol. V., 1910, pp. 357 and 403.

[4] Nikitin, *Mem. Russ. Geol. Com.*, New Series, No. 22, St. Petersburg, 1907.

replacements of a sheared igneous series; and Boutwell[1] has shown that the great pyritic mass of the Highland Boy in Bingham owes its origin to a replacement of limestone, the bedding of the latter being still discernible in the heart of the pyrites. The great pyrites masses of Mount Lyell in Tasmania are also, according to Gregory,[2] of metasomatic origin, occurring in places where schists have been crushed and shattered by intercrossing faults.

In South Africa the importance of this factor of ore-deposition is strikingly illustrated by the Witwatersrand Banket, and I have described elsewhere[3] the introduction of the gold of these deposits together with the iron-pyrites with which it is so intimately associated, as a process of metasomatic replacement. This replacement must have been subsequent to silicification, since the greater part of the pyritization is confined to the cement which was probably in a condition more suitable for solution than the pebbles. Occasionally, however, pseudomorphs of pyrites after quartz pebbles do occur[4] and fragments of slate are also found in a pyritized condition.[5]

Further instances of metasomatic replacement are furnished by some copper and lead-bearing sandstones of Triassic and Permian age. Thus the Russian Permian sandstone outcropping west of the Urals in Orenburg has been described by one of our members as containing copper-ores of pronounced metasomatic origin, not only the cement of the sandstones, but also plant-remains and tree-trunks being replaced by chalcocite and other copper minerals.[6] Such occurrences appear to be cases of low temperature deposition from meteoric waters at shallow depths.

In the foregoing brief summary of modern views on ore-genesis I have drawn attention to two principal lines of enquiry,

[1] Boutwell, *Trans. Amer. Inst. Min. Eng.*, Vol. XXXVI., 1905, p. 541.

[2] Gregory, *Trans. Austr. Inst. of Min. Eng.*, Vol. X., 1905, p. 26.

[3] Hatch, "The Auriferous Conglomerates of the Witwatersrand," "Types of Ore Deposits," San Francisco, 1911.

[4] R. E. Young, *Trans. of the Geol. Surv. of South Africa*, Vol. X, 1907, and Vol. XII., 1907, p. 82.

[5] Horwood, Mining and Scientific Press, Vol. 107, 1913, p. 611.

[6] Adiassewich, *Trans. Inst. Min. and Met.*, 1908, p. 509.

CLASSIFICATION OF ORE-DEPOSITS.

NATURE OF DEPOSIT.	VEHICLE OR AGENT OF ORE DEPOSITION.					
	a. MOLTEN MAGMAS.	*b.* GASES AND VAPORS above their critical temperatures.	*c.* DEEP-SEATED WATERS, whether of magmatic or meteoric origin.	*d.* VADOSE WATERS.	*e.* MECHANICAL AGENTS, such as moving water and wind.	*f.* CHEMICAL AND BACTERIAL AGENTS in seas, lakes and swamps.
1. IGNEOUS DIFFERENTIATES.	**Certain Massive Iron and Nickel Ores**, associated with basic igneous intrusions (*e. g.*, those of Sudbury in Ontario).					
2. CAVITY FILLINGS.	**Injected Tin Ores** (*e. g.*, tin pegmatites and tin elvans occurring on the margin of granite intrusions).	**Pneumatolytic Cavity-fillings** (*e. g.*, tin-quartz veins).	**Hydato-genetic Cavity-fillings** (many fissure-veins).	**Superficial Fracture-fillings**, such as gash veins in limestones and cavity-fillings (*e. g.*, the hæmatile ores of Cumberland)		
3. METASOMATIC REPLACEMENTS.		**Pneumatolytic Replacements** (*e. g.*, tin-greisens and many contact deposits).	**Hydato-genetic Replacements** (many veins and massive deposits; also the Rand Banket).	**Some Lead and Zinc Ores in limestones. Iron ores replacing limestones** (*e. g.*, Cleveland). Some **lateritic iron** and **manganese deposits. Secondary enrichments of copper ores.**		
4. STRATIFIED DEPOSITS.			**Possibly some sedimentary deposits in which the cementing materials are ores of the metals.**	**Some Lead and Copper Ores, interstitial in sandstones and shales.**	**Mechanical Concentrates in bedded deposits** (*e. g.*, gold and platinum placers, stream-tin, iron-sands, detrital laterites and other metalliferous gravels and sands).	**Chemical and Bacterial Sediments** (*e. g.*, lake and bog iron ore; clay iron-stone and other sedimentary siderites, bog manganese ore and other sedimentary manganese ores).
5. RESIDUAL DEPOSITS.				**Mantle-deposits** (*e. g.*, pisolitic and nodular ores of iron (Bilbao and Appalachian hæmatites and limonites), of manganese (psilomelane) and of aluminum (bauxite)).	**Eluvial Gravels formed near the outcrop of veins** (*e. g.*, those of gold, wolfram, cassiterite, galena and zinc ores).	

the one dealing with the agent or vehicle by means of which the metals have been collected, conveyed to, and deposited in the places where they are now found, and the other with the nature of the concentrate formed in the course of these processes.

Considering the latter first: ore-deposits are found to be either

1. Igneous differentiates.
2. Cavity-fillings.
3. Metasomatic replacements.
4. Stratified or sedimentary deposits.
5. Residual deposits.

Of these the sedimentary deposits comprise marine, lacustrine and fluviatile accumulations, including placers.

Coming now to the agent or vehicle of concentration, these are found to be

(*a*) Molten magmas.
(*b*) Gases and vapors above their critical temperatures.
(*c*) Deep-seated waters whether of magmatic or of meteoric origin.
(*d*) Vadose waters.
(*e*) Chemical and bacterial agents in lakes and seas.
(*f*) Mechanical agents, such as moving water and wind.

It is possible by combining the facts elicited by these two lines of enquiry, to formulate a genetic scheme of classification. For example, cavity-filling may be due to igneous injection, to gases and vapors above their critical temperatures, to deep-seated waters or to vadose waters; again metasomatic replacement may be brought about by gases and vapors, by deep-seated waters, or by vadose waters. By arranging these two series of relationships in vertical and horizontal columns respectively all the various types of ore-deposits are obtained at their intersections; and in this way I have been led to the following classification.

RELATIVE TO AN EXTENSION OF THE MENOMINEE IRON RANGE EASTWARD FROM WAUCEDAH TO ESCANABA, MICHIGAN.

R. C. ALLEN.[1]

The Menominee Iron Range of Michigan, so far as known, includes a folded series of Huronian rocks trending a little south of east from the Menominee river in T. 40, R. 31 to the longitude of the village of Waucedah, Dickinson county, a distance of about 19 miles. The Lower Huronian is represented by a series of thick formations of quartzite (Sturgeon) and dolomite (Randville), the Middle Huronian by cherty quartzite not exceeding 70 feet in thickness, and the Upper Huronian by a vast thickness of slate (Hanbury) overlain by volcanic green schists (Quinnesec) and carrying two productive iron bearing formations in basal horizons. The Huronian series lies unconformably on the Archean Complex.[2]

The areal distribution of the iron formation is shown on the accompanying figure.

It is reported that drilling a short distance west of the Menominee river in Florence county, Wisconsin, failed to locate the iron formation of the southernmost belt (see Plate III) in the territory where it may have been expected to occur judging from its structure and strike between the city of Iron Mountain and the river. In the opposite direction the iron formations are overlapped by Cambrian sandstone in the vicinity of Waucedah. East of Waucedah the thickness of the Paleozoic rocks increases, presumably rather regularly, to about 800 feet in the vicinity of Escanaba.

It has been obvious for many years that the Menominee range Huronian series, including the iron formations, extends an un-

[1] State geologist of Michigan.

[2] For description of the geology of the Menominee iron range see Monograph 52, U. S. G. S., page 328–46.

known distance east of Waucedah beneath the flat lying Paleozoic formations. The magnetism of certain of the Huronian rocks, particularly (but not exclusively) the iron formation, furnishes the only means short of actual drilling or underground exploration by which they may be traced into the Paleozoic territory. Magnetic surveys of a part of the area east of Waucedah have been made by certain mining companies, and the results of some of their work were placed at the disposal of the writer. The economic importance and scientific interest of the problem furnished the incentive to complete the magnetic survey of the range eastward to Lake Michigan.

The survey was executed in the field by L. P. Barrett, assisted for a portion of the time by H. J. Allen. Where information was available efforts were extended only to checking the accuracy of former surveys. The results are shown in a general way on the accompanying plate.[1]

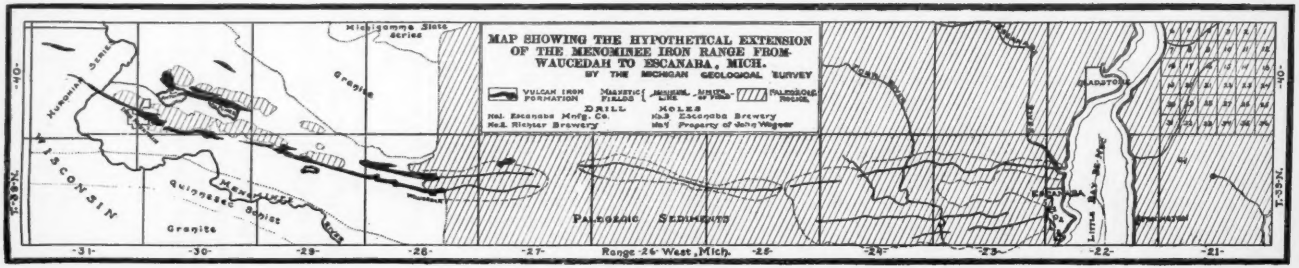
Conclusion.—It will be seen that the magnetic belts which are coincident with the two separate belts of iron formation near Waucedah extend eastward without break for about six miles. The assumption that these belts have the same relation to iron formation beneath the Paleozoic rocks that they have to known occurrences at Waucedah and westward seems warranted. It is, however, unsafe to conclude that the magnetic belts further east to Little Bay de Noc are all or even partially underlain by iron formations of the ore bearing type of the Menominee range. From their general and linear-symmetrical characters it may be inferred that the magnetic rocks are folded sedimentaries and that they contain iron, at least partly, in the form of magnetite. But the magnetic beds may or may not be the stratigraphic equivalents of the iron formations of the Menominee range. In this connection the reported extension without break of a magnetic belt from the known iron formation at the opposite end of the range westward into magnetic slates, as shown by drilling, is instructive.

A recent drill hole in the general projection of the northern-

[1] Large scale plats showing the magnetic observations may be obtained on application to the state geologist, Lansing, Michigan.

most magnetic belt on Stonington Peninsula in the SW. ¼ of the NW. ¼ of Sec. 8, T. 39 N., R. 21 W. encountered dense, gray, vitreous quartzite similar to the Sturgeon (Lower Huronian) quartzite of the Menominee range after penetrating 780 feet of Paleozoic beds. It is reported that iron formation was penetrated at a depth of 732 feet at the Escanaba brewery, granite at 810 feet at the Richter brewery, and granite at 931 feet at the plant of the Escanaba Manufacturing Company, all in the city of Escanaba. There is little doubt that the above figures represent in each instance the approximate thickness of the Paleozoic rocks, but inasmuch as no records of the drillings were kept and no samples of the cuttings or cores preserved of the holes in Escanaba little credence should attach to the hearsay reports of the character of the underlying pre-Cambrian rocks.

From the evidence available it may be fairly assumed (1) that the magnetic belts mark the course of pre-Cambrian sedimentary rocks from Waucedah to Escanaba, (2) that these rocks contain magnetite, (3) that the magnetic beds are probably associated with other sedimentary formations which have little or no magnetism, (4) that it is not improbable that the succession and in a general way the structure of the pre-Cambrian beds may be closely related to those of the Menominee range west of Waucedah, and finally (5) that the occurrence of productive iron formation may be related in some degree and in some place or places between Waucedah and Escanaba to the magnetic belts. In advance of actual drilling operations no further assumptions are warranted.


MAP SHOWING THE HYPOTHETICAL EXTENSION
OF THE MENOMINEE IRON RANGE FROM
WAUCEDAH TO ESCANABA, MICH.
BY THE MICHIGAN GEOLOGICAL SURVEY
VULCAN IRON FORMATION
MAGNETIC FIELDS
MINERAL LINE
LIMITS OF FIELD
PALEOZOIC ROCKS
DRILL
No1 Escanaba Mnfg. Co.
No2 Nicolet Brewery
MOLES
No3 Escanaba Brewery
No4 Property of John Wagner
PALEOZOIC SEDIMENTS
Michigamme Slate Series
Granite
Quinnesec Series
WISCONSIN
Range 24 West, Mich.
T.39N.
T.38N.
-31-
-30-
-29-
-28-
-27-
-26-
-25-
-24-
-23-
-22-
-21-

MINE WATER COMPOSITION AN INDEX TO THE COURSE OF ORE BEARING CURRENTS.

ALFRED C. LANE.

A year ago (43, LXXXII.)[1] I read a paper, which I did not care to have published at the time, touching on stagnant mine waters,—a branch of the subject of this paper, with the hope of eliciting further facts. I am glad to contribute a revision of it to this discussion. That one may quickly know what kind of facts should be sought, the conclusions which seem attainable will be given first and then sources of some of the classes of facts.

1. Change of chemical character by diffusion apart from circulation is slow at ordinary temperatures, more rapid at high temperatures.

2. At relatively shallow depths (1,000–2,000 feet or less) undisturbed strata are filled with saline water largely connate and relatively stagnant. Some seeming exceptions may be due to circulation from old land surfaces now represented by unconformities. Circulation increases the proportion of sodium to chlorine.

3. Therefore, currents may be indicated by the changed character of the water, even a long time after their circulation.

4. Up currents are likely to affect the country rock more than down currents both (*a*) because diffusion is more active at high temperatures and (*b*) because they are likely to have a much greater difference of head from that in the country rocks than in the case of downward circulation.

5. Waters of lodes—mine waters—show the effect of circulation in their chemical character, those which have circulated up being more highly charged with SiO_2, and less charged with $CaCO_3$.

[1] This paper was presented by request of the Chairman of the Committee on Mining Geology at the annual meeting of the American Institute of Mining Engineers in New York, Feb., 1914. It is published here by permission of the author and by courtesy of the American Institute of Mining Engineers.

6. Systematic testing of water of the mine and that leached from drill cores of the country rock, or flowing from drill holes, may give suggestions worth while.

1. *Diffusion is Slow.*

To the data of the Encyclopedia Britannica (Art. "Diffusion," p. 258), *e. g.,* that for salt and water the diffusivity $K = 0.355$ cm²/hour at 5° C. or at 14°, 35 C. 1.020–0.932 cm²/day, *i. e.,* that if the content of salt in the water decreases 1 per cent. in 1 cm. then the velocity of the diffusing salt will be about .01 cm. per day, we may add illustrative data such as that found in *Science* (Oct. 17, 1913), that it would take over 1,000,000 years for Lake Constance to be saturated with air, if it acquired its supply only by diffusion from the atmosphere.

Other data will be found in Chamberlin's Geology and tests by the Wisconsin and Michigan State Geological and Biological Surveys[1] have shown how very great is the difference in composition of lake water when the upper water is warm, the lower cold and there is no circulation.

More germane to our discussion is the wonderful difference in the chemical character of the water found by Emmons in the sumps of mine shafts.[2]

All these data, it is to be noted, refer to a solid mass of water. How much greater must be the difficulty of diffusion when it is through the pores of a porous rock, the porous fluid occupying, at most, but a small fraction of the space, and when, conceivably, diffusion, as well as circulation, is hindered by capillary forces.

This *a priori* conclusion is confirmed by plenty of illustrative facts.

For instance, fragments[3] of copper bearing conglomerate,

[1] Michigan Geological Survey Report for 1907, p. 197.

[2] U. S. G. S. Bull. 529, pp. 60–67. Especially analyses 10 and 11, from the top and bottom of No. 20 Shaft, Ducktown; 12 and 13 from the top and 37 feet below of the Callaway Shaft, same place; 14 to 16, water from the 300, 400 and 900 feet level of the Capote. It will be noticed, for instance, that in the Callaway Shaft the difference in composition between the surface water and that 37 feet below shows that the surface water contains twice as much sulphuric acid as that further down.

[3] Michigan Geological Survey, 1909, Pub. 6, Vol. 2, pp. 806 and 808.

weighing about a pound, soaked over successive nights in about a pound of distilled water each time gave Koch and myself the following results for chlorine (Ca:Cl was about .485, the rest mainly NaCl).

	Osceola Amyg., 851 Grams, Cl, Gr.	Calumet Congl., 555 Grams, Cl, Gr.	Calumet Congl., 500 Grams, Cl, Gr.	Mainly Copper, 242 Grams, Cl, Gr.
1st washing	2.5577	3.6514	3.4209	.3428
2d washing	.5339	.4786	.3155	.0482
3d washing	.3828	.1489	.1064	.0319
4th washing	.2283	.0851	.0523	.0177

Obviously the massive copper and coarse-pored conglomerate are losing their salts more rapidly than the fine-pored amygdaloid.

5. The enormous difference in the saltness of the lodes of the Challenge Mine[1] at the same level and less than 200 feet apart, though due, as we shall see, to circulation, is probably not due to

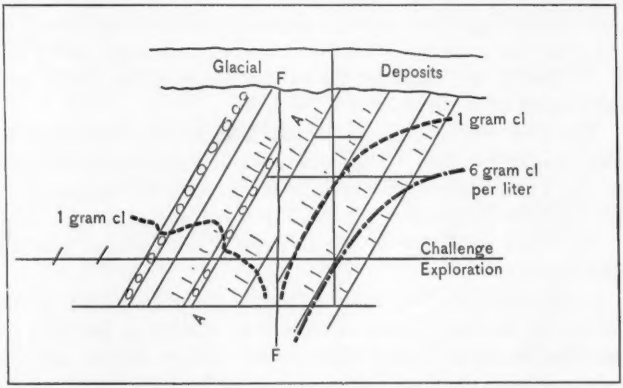


FIG. 77. Sketch adapted from Fig. 59, p. 834, Vol. II., Pub. 6, Geol. Surv. Michigan, 1909, showing the Challenge exploration of the St. Mary's Mineral Land Co., in Sec. 22, T. 5-3N., R. 35W., R. R. Seeber, Supt. The isochlors for 1 gram per liter of chlorine and 6 grams are shown by heavy broken lines lower near the nearly vertical fault F–F, which has displaced the bed A as shown. The strike of the fault and a plan is shown in Plate XI., *loc. cit.* Reduction about 1:6000.

[1] Fig. 59, *loc. cit.*

any recent circulation, for the rock is covered with drift, and it could not have existed if the effect of diffusion were not very slow. Similar facts are too numerous to mention. For instance, in the Victoria Mine, 19th level crosscut, 510 ft. north of the lode, Cl is 660 per million, 538 ft. south, Cl is 2,920 per million.

Numerous wells[1] find alternate streaks of fresher and salter water which could hardly exist, in the relatively undisturbed strata in which they occur, were not diffusion slow.

2. *At relatively shallow depths (1,000 to 2,000 ft. or less) undisturbed strata are filled with saline water largely connate and relatively stagnant.* The words "in general" are used so that I may not be understood to deny the occasional existence of gas filled or fresh water strata, but like the Tamarack rock just cited much rock called "dry" is really saturated with brine, but the pores are few and small, the rock impervious, and easily dried on the surface. In proof of this statement, I shall not try to go outside the United States, which is a large enough sample of the world, involving most of the geological column, except merely to call attention to the worldwide occurrence of salt water under oil. I will then briefly run over the various states of the Union and the sources of information for them.

The New England states contain few strata which may be classed as undisturbed. The extremely salt water found by Clapp in the Vinal Haven granite may be connate, in the sense of belonging to the granite. It certainly is not a normal sea water. It shows the possibility of the presence of such waters, even in such regions.

In Massachusetts, the water of the Boston Basin, which is, of course, by no means undisturbed, but as little so as any part of the state, is salt at a very slight depth. Beside the old analysis (2) at a depth of 1,700 feet, reported by T. S. Hunt,[2] I owe to Professor F. W. Durkee some data regarding recent shallower wells which show the same water, *e. g.*, (1) from Jas. F. Morse and Co., 66 Norfolk Ave., Roxbury, 504 feet deep.

[1] "Saline Artesian Waters of Atlantic Coastal Plain," U. S. G. S. Water Supply Paper 258, p. 81. See also references below.

[2] Proc. Boston Soc. Nat. Hist., Vol. 17, pp. 486.

	(1)	(2)
Cl	1,736 parts per million	10,823
SO_4	72	1,350
CO_3	small o?	
(NaK)	512	3,380 70
Ca	326	2,404
Mg	142	760
$SiO_2 > (FeAl_2)O_3$	22	

Other deep wells in the Boston Basin over 500 feet deep, *e. g.*, at the soap works in East Cambridge, show also a more or less salty water and, so far as we know, much above 1,000 feet the waters are salt.

Then we also have salt water from artesian wells in the Triassic of the Connecticut Valley.[1] Unfortunately, the depth at which the salt first appeared in the 3,700-foot well at Northampton is not definitely known, and the tables given by Gregory[2] show no analyses of water from wells between 1,000 and 2,000 feet. The shallower wells are, however, said to be highly mineralized.

Passing down to New Jersey, we have the salt water of the New Jersey[3] Passaic 2,100 ft. well at 1,000 feet, but there is water at 900 feet also in the Triassic, and various waters of the coastal plain cited by Woolman, etc., are often salt in wells less than 1,000 feet deep. The deepest which has been analyzed at Atlantic City, at 1,150 ft., has 331 parts per million chlorine and is mainly sodium chloride, a typical dilute connate water.

The geological conditions remain similar throughout the Atlantic coastal plain of relatively undisturbed deposits.

Delaware: Sanford[4] cites a well at Lewes, Sussex Co., with "fresh water" at various levels down to 750 feet, salt water at 891, 950 and 1,080 feet.

Maryland: Sanford cites a well, 1,500 feet deep, at Pocomoke, Worcester Co., which has 1,180 per million Cl, but the main salt

[1] Reported by Emerson in his "Geology of Old Hampshire Co.," U. S. Monograph XXIX., pp. 380–89.

[2] U. S. G. S. Water Supply Paper 232, pp. 120, 121, 178.

[3] Annual Report State Geologist, 1890, p. 270; 1888, p. 75.

[4] U. S. G. S. Water Supply Paper 258, p. 78.

horizon is said to be at 480 feet. The water at 1,200 feet is said to be fresher, however.

Virginia has numerous wells cited by Sanford[1] with over a thousand per million of Cl and nothing but salt water noted below 285 feet. At Lambert Point, near Norfolk, at 616 feet is a well with Na_2CO_3 as well as NaCl. At 1,038 feet and 1,070 feet respectively in the Norfolk artesian well (analyzed by Professor Froehling, Norfolk, Va.) out of 195.1203 grains per U. S. gallon, mineral matter respectively 213.0298, there are 96.5997 respectively 100.4090 Cl,—say 1,720 Cl out of 3,630 mineral solids.

North Carolina at Wilmington has one well which is said to have had fresh water at 1,000 feet, but, generally, the water is salt at much less depths, 300 feet and deeper in the Miocene and Cretaceous.

South Carolina: At Charleston, there is said to be a well put down in Cretaceous to 1,950 feet in 1879 with water at 960, 1,000, 1,557, 1,590, 1,862, 1,880 feet and yet only 121 per million Cl.

Georgia: McCallie in Bulletin No. 15[2] of the Geological Survey of Georgia gives a full report on the underground waters of Georgia. On pages 48 and 49, he summarizes the result, that the greater the depth the greater the mineral matter, that relatively soft waters can be obtained in the Cretaceous down to 1,200 feet. At Savannah even a well as deep as 1,500 feet has but 11.5 per million Cl. This is, however, more than the 500-foot wells. The bottom strata are presumably Cretaceous. At what depth this water comes is uncertain; comparing with Thomasville (p. 177), probably only 200 to 400 feet down. It is all the more striking that we find a strong calcium chloride water in the granite (pp. 203, 207, 208) like that found in Maine, and at the Storm King Crossing.

In Florida, we have an unusual number of salt waters compared with Georgia. The Fifth Annual Report, 1913,[3] just issued, gives a full account of the water supply of eastern and southern Florida.

[1] U. S. G. S. Water Supply Paper, 258, p. 78.
[2] See also Bull. 20, pp. 103, 109, 147.
[3] Geological Survey of Florida.

There is a well at Palm Beach, which, from 846 to 1,212 feet, but mainly at 1,085 feet to 1,088 feet, struck a water with 1,337 parts per million Cl, 431 SO_3, 3 PO_4, no CO_3, 195 HCO_3, 835 NaK, 112 Mg, 102 Ca, 2 FeAl, 17 SiO_2, loss 357, total 3,000.

Wells at Key West at 1,010 and 1,200 feet also struck salt water. Numerous shallower wells (as, for instance, at Cocoa, pp. 235–6) show a mixture of the strong salty waters with waters containing carbonate of soda or sulphates, such as are more prominent in Georgia.

The strongest well in the state seems to be that at Titusville (p. 244) which has 11,879 parts per million Cl, 6,542 NaK, 547 SO_4, 8 SiO_2, 669 Mg, 637 Ca, 3 FeAl, 1,380 loss, 23,060 total.

In this well, the water comes from about 145 feet only, but is not quite the same as sea water. Many of the shallower wells contain salty water.

The main source of the deeper waters is the Vicksburg limestone of the Oligocene. The Cretaceous waters are not known. Judging from what is found in Georgia, however, they might not be as salt.

Coming around to Alabama, W. O. Crosby informs me, by private communication, that there is strong salt water at 2,900 feet or less, in the older Paleozoics where the Appalachian folds are dying out and crossing the Cincinnati uplift and that there is, also, salt water in some minor domes nearer the surface in the Tertiary strata.

In Louisiana, the "yellow waters" come at 600 to 900 feet, while at 1,250 feet the water is salt in New Orleans.[1] The presence of salt in salt domes has been fully discussed by Harris[2] and it seems quite possible that, as he suggests, in some cases the salt is derived by upward circulation. However, that the deeper strata are, in general, salty is clear.

If we pass up the Mississippi Valley into the great belt of interior states, we find everywhere salt waters at relatively scant depths in the Paleozoic rocks. I have studied most carefully the

[1] Harris, U. S. G. S. Water Supply Paper 101, p. 45.

[2] Economic Geology, Vol. IV.; Louisiana State Survey Bull. 7.

waters of Michigan and there I found that while it is possible, at times, to have fresh water underneath salt, as in Huron County, in the Marshall sandstone underlying the gypsum and salt formations (a good illustration of how slow changes of diffusion are), yet by the time one has reached a depth of less than 1,000 feet, we have, in all cases, obtained water much stronger than any of the thirty-seven mine waters cited by Emmons, the highest of which has but 843 parts per million of chlorine. It will be noticed, too, that this particular one, which is very much higher than any of the other analyses cited by Emmons, is 1,125 feet from the shaft.

Ohio and Indiana have been reported on by Leverett,[1] who says that the deep wells are usually strongly saline. The wells at Corydon, Gosher, Huntington, Kokomo, etc., show that salt water is struck between 1,000 and 2,000 feet, if not higher up.

The head of the Cretaceous and Tertiary embayment in Illinois, Kentucky, and Tennessee is treated in Water Supply Paper 164. A water 600 feet deep at Wickliffe has four times as much Cl as one at 147 feet.

The deep Paleozoic waters of Illinois and Iowa are more fully described by Leverett.[2] Here we find in the St. Peters or Potsdam sandstone, one real exception to our rule: While the strata are salt above it, wells in this bed between 1,800 and 2,000 feet down are still so fresh as to suggest either that it was laid down in fresh water, or, during a period of uplift shortly subsequent, leached when close to the surface.

As an illustration of how soft such a water under the salt beds of the Salina formation can be, an analysis of water from the Macomb Water Works well at 1,135–1,360 feet is, perhaps, best, as the upper waters were most carefully cut off.

Though much fresher than shallower waters, there is still much more chlorine than in surface waters.

Kentucky waters[3] show that the St. Peters sandstone there has a load of chlorine. The 1,250-level at Newport has 6,400 per

[1] 18th Annual Report U. S. G. S., Pt. IV., *B*, pp. 488–493, 495.
[2] 17th Annual Report U. S. G. S., Pt. II., p. 810.
[3] U. S. G. S. Water Supply Paper 233, p. 212, etc.

Cl	541.8	per million.
SO_4	832.6	
CO_3	289.9	
SiO_2	10.5	
O	273.2	
Na	808.6	
K	23.7	
Ca	158.1	
Mg	67.2	
Fe	1.3	
Al	7.0	
	3,007.6	

million Cl, 3,700 NaK. The ratio of Na:Cl is, however, higher than in waters nearer the surface, *e. g.*, a 125-foot well at Donerail in the Lexington formation, so that there is probably some surface sodium sulphate water mixed.

The Texas waters[1] are abundant, but even at depths much less than 1,000 feet are likely to be strongly mineralized. For instance, at Bowie, at 640 feet, there is already 972 per million Cl. The waters are generally a mixture of downward working sodium sulphate waters with connate waters.

Missouri, whose waters have been studied by Shepard,[2] has both Tertiary and Paleozoic waters and shows the effect of circulation from land surfaces now represented by unconformities. Very strong waters come in less than 1,000 feet (pp. 81–84), but at about 800 feet, too, there are strong sodium sulphate waters, such as Lindgren ascribes to vadose waters of arid regions, like the analysis of the St. Peters water just given.

Wisconsin has very similar conditions to Illinois,[3] but beside the connate salt water, the sulphate waters of the Potsdam and St. Peters are more important, and there is more probability of past or present circulation.

Passing on to the Great Plains, the waters of which have been studied by Darton,[4] we find that although here in the Dakota

[1] U. S. G. S. Water Supply Paper 317, pp. 21, 34, 42.

[2] U. S. G. S. Water Supply Paper 195; *Am. Jour. Sci.*, 1908, p. 452.

[3] Wisconsin Survey, Vol. 1, p. 308; also report of City Engineer of Madison.

[4] 17th Annual Report U. S. G. S., Pt. II., p. 677 Dakota, 588 Colorado; 18th Annual Report, Pt. IV., p. 561 Dakota; 19th Annual Report, Pt. IV., p. 719

sandstone, we have a chance[1] for a deep-seated artesian circulation, the waters run relatively high in chlorine, though sodium carbonates and sulphates by their presence show a large mixture of downward working waters of the arid type, *e. g.,* Pierre 1,150–1,160 feet, with 2,805 parts per million NaCl.

To give an explanation for this universally distributed chlorine, if the fact be granted, is not essential to our argument. It has been suggested that with some intraformational diffusion and circulation, it is very largely connate,—sea water with perhaps occasional streaks of other water from land strata and, at times, desert strata buried, too. I would not deny that the chemical character of these connate waters has been changed. A certain amount of absorption and hydration, a certain amount of generation of organic material and precipitation of sulphur from calcium sulphide I have already argued as probable,[2] but the accumulation of calcium chloride in rocks (sandstone rocks as well as limestone rocks) seems to me hardly possible, by mere circulation, except by circulation through such a rare type of deposit as that of Stassfurt. Washburne, however, gives another theory elsewhere discussed.[3]

Acid volcanic vapors or waters, of Cl, HCl or Fe_2Cl_6 could produce $CaCl_2$ by reaction on lime producing rocks, and it may be the last residue in the crystallization of granite. Again acid chlorine waters or calcium or ferrous chloride waters meeting sodium carbonate or sulphate waters of the arid land type could produce waters containing sodium chloride, *but* there would not be a larger amount of chlorine than was contained in the original water.

I can not accept, for this reason, the method of accumulation of the chlorine that has been suggested by Van Hise and Leith or by Steidtman in Monograph 52. Of these waters they say: "Their

Nebraska; Professional Papers 17, 32, 52. University of Colorado Bulletin, Vol. XII., No. 5, p. 17, shows the amount of Cl in the Dakota sandstone in southeastern Colorado, varying from 18 parts per million at 340 feet down to 125 at 1,400 feet depth and 2,615 at 1,545 feet depth.

[1] 17th Annual Report U. S. G. S., p. 666.

[2] Report on Huron Co., Mich. Geol. Sur., Vol. VII., Pt. II., p. 141.

[3] Bull. A. I. M. E., March, 1914. p. 375.

characteristics seem not to be related to certain kinds of rocks or ore deposits, but to depth and stagnant conditions. Chlorine is present in minute quantities in original igneous rocks and in nearly all surface waters. Its salts tend to remain in solution, while the salts of other acids are more largely precipitated. With a given amount of water, there seems likely to be, therefore, a progressive relative accumulation of chlorine salts. Such is the case in salt waters at the earth's surface, where a large factor in the accumulation is the lack of sufficient circulation to carry off and dilute the salt waters that are developing by evaporation. In deep underground waters, there is essentially the same condition of stagnancy and, therefore, we suggest progressive accumulation of soluble chlorine salts."

To this argument that attributes these salt waters to an accumulation by solution through slow circulation, there are serious objections. In the first place, there is lacking one vitally important factor in the accumulation of salt waters at the surface of the earth—to wit, evaporation—and there can be no increase in the amount of chlorine in a given amount of water (except in so far as the water is absorbed by hydration, which goes on in sedimentary rocks mainly before or during, rather than after, burial as Barrell has suggested in discussing the role of limonite and hematite) or chlorine is dissolved from a solid state. Solid minerals that contain Cl are rare, and I know of no analyses that show leaching. The "relative accumulation" would be relative to the other salts, the sulphates or carbonates, but *not relative to the water.* The expression of the constituents as percentages of "total solids," as is often done, is for this reason misleading. It is also true that the amount of individual constituents is often better known than the total salinity. Moreover, if in deep underground waters, there is a "condition of stagnancy," then it is very unlikely that the original waters could be thoroughly removed.

Secondly, in analyses of waters from mines where there has been secondary enrichment and, therefore, circulation downward, we see no indicated accumulation of Cl. In but one of the mine water analyses cited by Emmons,[1] in which there has been a

[1] *Loc. cit.*, pp. 60 and 61.

great accumulation of soluble sulphates, has there been anything like such an accumulation of chlorides. Many of them are notably low in Cl. We ought, to be sure, to find other than salt waters in the buried strata, fresh water from fresh water deposits at times or from circulation from old land surfaces now represented by unconformities and alkali waters from buried desert surfaces. But the rarity of such waters below a thousand feet depth indicates that marine deposits are commoner and that occasional streaks of other kinds may be more or less altered by diffusion. The compositions of waters deep in the Dakota and St. Peters sandstone, in the references given above, indicate that in a slow and long and deep downward circulation, the water is fresher than the strata above or below and, *also, that such downward circulation,* whether from the present surface or from some surface of a previous age, now marked by a disconformity, *tends to increase the ratio of sodium to chlorine. The same change appears in the Keweenaw copper mine waters* as shown in Plate IV. The progressive accumulation of Na instead of Ca or Mg which are likely to be precipitated out in many gangues is the fact to which Van Hise's argument above cited applies; and this is characteristic of circulation, its absence of stagnation.

The change in the chemical character of the waters of the Keweenaw copper mines from the circulating to the stagnant zone is so sharp or so great that I have not been able to express it in a single diagram. In the upper levels for the first 1,000 feet or so, there is present plenty of water, as in most mines, and a perpetual drip and, therefore, much pumping.

A plan of the Victoria Mine shows this (Fig. 78); as in many mines this belt goes down below the 10th level. In other cases, as in the Challenge Exploration (Fig. 77), it is very much less deep and salt water is found in 300 or 400 feet.

The waters of this first belt vary a good deal in character. Sometimes they appear to be really surface waters (An 1), like those of the overlying gravels which contain numerous limestone pebbles. In that case, calcium carbonate is the leading salt and Ca is great, relative both to Cl and to Na, and CO_2 is high. At

other times (An 2), they are really quite soft and sodium silicate or carbonate seems to be an important factor,—that is, they are the kind of waters that would be naturally produced by the leaching of traps and felsites. In both types of water, the specific gravity

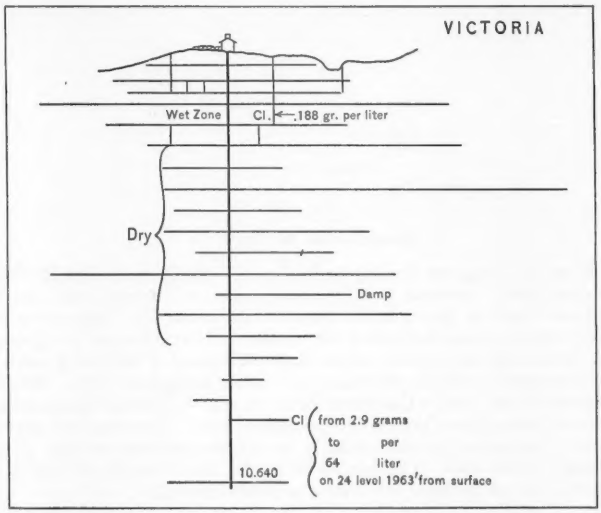


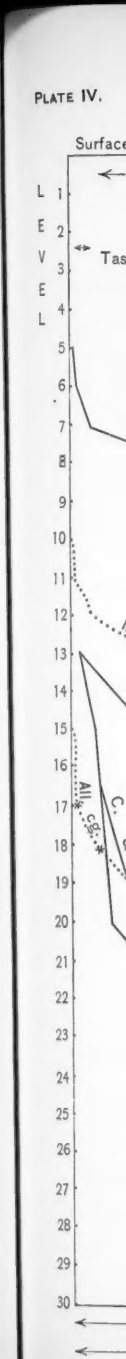
FIG. 78. Sketch after engineer's map of Victoria Copper Mine, Michigan, showing the distribution of Cl. See pp. 85–86 of Pub. 6, Geol. Surv. Mich., 1909.

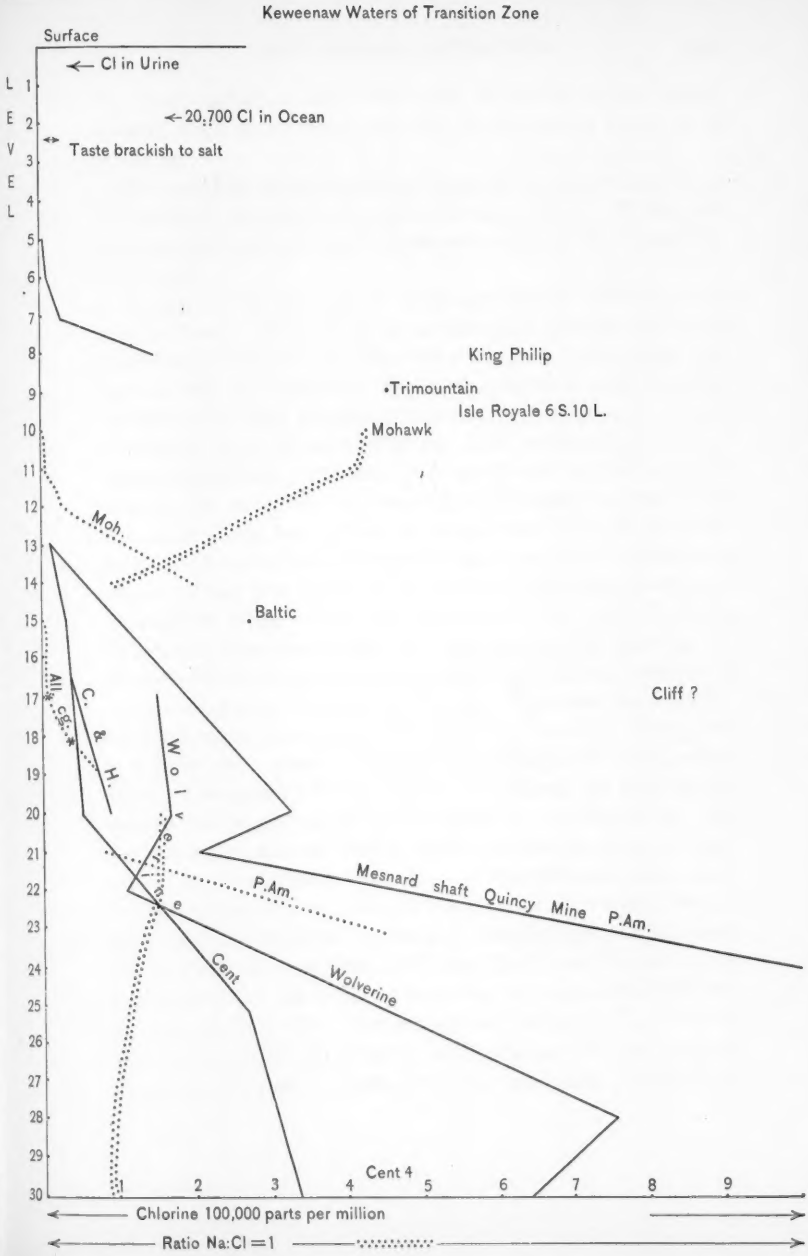
is practically 1 and the total solids are much less than a gram per liter, usually less than 500 parts per million, and the chlorine is so low that one can not say that it might not be produced by organic contamination (Fig. 79), though one may also suspect admixture of relics of the deeper type of water.

Next below this zone of relatively free circulation, extending well down toward the newer openings of the mine (shown on the Victoria diagram (Fig. 78) by the belt marked Dry) the levels yield no water, though freshly broken rock and bands of amygda-

Explanation of Plate IV.

Plate IV. Diagram showing distribution of "middle waters" of Michigan Copper Mines. Abscissas to right show amounts of Cl found in the water in different levels as shown in the vertical scale on the left. Those from the same mine are connected by lines full or dotted. Near the top of the diagram the distances to the points of arrows show the amount of chlorine in urine in the ocean and in distinctly brackish or salt tasting water respectively. Moh. = Mohawk Mine, Cent. = Centennial Mine, P. Am. = Pewabic Ammygdaloid, not only in the Quincy but also in the Franklin Mine. The dotted line labelled All. cg. represents bits of chlorine in the allonez conglomerate lode of the Franklin Junior Mine. The lines of double dots show the ratio of sodium to chlorine for the Mohawk and Wolverine Mines especially.




Keweenaw Waters of Transition Zone
Surface
Cl in Urine
20,700 Cl in Ocean
Taste brackish to salt
LEVEL
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
King Philip
Trimountain
Isle Royale 6 S.10 L.
Mohawk
Moh.
Baltic
Cliff ?
All. Cliff
C. & H.
Wolverine
P.Am.
Mesnard shaft Quincy Mine P.Am.
Cent.
Wolverine
Cent 4
1
2
3
4
5
6
7
8
9
Chlorine 100,000 parts per million
Ratio Na:Cl = 1

loid may appear so damp that even in the smoke and grime covered walls of crosscuts they may be recognized by beads of moisture.

On the whole, however, evaporation due to the circulation of air takes off the water and may even make the face of the rock dry and dusty, but I do not think there is any level where the fresh rock is dry.

The farther down we go, the wetter the rock becomes and, from time to time, pockets of water are struck in mining which may flow fairly freely at first. But they show their lack of freer connection with the surface by the fact that the flow soon dwindles. As soon as we take samples of this water, we find we have quite a different story, shown on Fig. 79. The amount of salt has increased immensely. The chlorine is usually above 5,000 parts per million, *i. e.*, more than is contained in sea water or urine whose content in Cl has been put on for comparison. Fig. 79 shows the levels at which the zone of rapid increase occurs for a number of mines. When first struck the amount of (salt) *sodium* chloride is relatively large. With increasing depth, the ratio of sodium to chlorine drops and approaches .084 and calcium chloride and bromide becomes more important until it approaches a pretty pure and constant type, as shown by Fig. 79. The exact concentration of this stronger water is subject to irregular variation. Both dilution by surface waters following the mining down and concentration by evaporation play a part. In general, as might be expected, the deeper waters are stronger but not regularly. The surface waters have so little in them that dilution of the stronger waters by them changes the ratio of the different constituents in the same proportion. Now in Fig. 79, the analyses are arranged according to ordinates downward, proportionate to the total solids, while the proportion of Cl and Br, Ca and Na are set off to the right. A line is drawn from the dot representing the proportions of Na to that representing this amount of Ca. We see that the positions representing the Cl, Ca and Na are arranged along straight lines radiating from the zero point. That means

that they are almost exactly in proportion to the total solids so that there is no variation in composition except the variation in concentration that may be the effect of evaporation or accidental dilution. We see that the strongest waters are so strong a solution of calcium chloride, which has a strong affinity for water, that it is not likely that they would tend to lose any more water.

I have said that the signs which indicate the proportion of Ca, Cl and Na are in a line. But we note that that is not strictly true. Some of the lesser concentrations have less Ca and more Na and these are waters from relatively shallow depths and from the conglomerates, where there has been more circulation. I have called attention to the fact that in the deeper levels and prior to the formation of copper, lime zeolites and other secondary minerals appear, while later than the copper, alkaline zeolites occur. It seems likely, therefore, that this sodification of the mine water, which *can not* be due to mere mixture of the upper and lower waters by circulation, may be due, in part, to ionic migration of the Na and, in part, to an attack upon the rock by the mine waters, one feature of which is a precipitation of native copper, another feature the leaching of sodium silicate, sometimes to be reprecipitated in zeolites, oftener to be divided into reprecipitated quartz, silica available for epidote, etc., and sodium left in the mine waters.

Many others besides Darwin[1] have indicated that it is probable that most of the strata preserved were formed during times of subsidence and, therefore, generally, though not always, in brackish water. I can see no escape from the conclusion that both the water and the chlorides contained therein, especially the earthy chlorides, are, for the most part, connate. All the analyses I have found to study seem to show that circulation tends to precipitate lime in the ubiquitous calcite. I await with interest any plausible reactions that will account by circulation for the earthy chlorides. The ocean, however, now has them and seems always to have had them. It is true that such waters are very similar to

[1] "Origin of Species," p. 291.

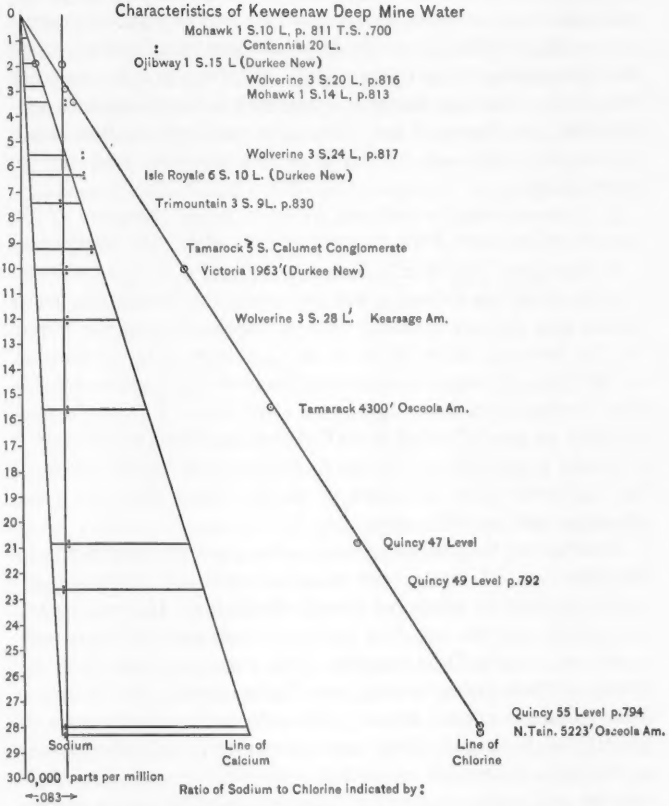

Characteristics of Keweenaw Deep Mine Water
Mohawk 1 S.10 L, p. 811 T.S. .700
Centennial 20 L.
Ojibway 1 S.15 L (Durkee New)
Wolverine 3 S.20 L, p.816
Mohawk 1 S.14 L, p.813
Wolverine 3 S.24 L, p.817
Isle Royale 6 S. 10 L. (Durkee New)
Trimountain 3 S. 9L. p.830
Tamarock 3 S. Calumet Conglomerate
Victoria 1963' (Durkee New)
Wolverine 3 S. 28 L. Kearsage Am.
Tamarack 4300' Osceola Am.
Quincy 47 Level
Quincy 49 Level p.792
Quincy 55 Level p.794
N. Tain. 5223' Osceola Am.
Sodium
Line of Calcium
Line of Chlorine
0,000 parts per million
.083
Ratio of Sodium to Chlorine indicated by :

FIG. 79. A graphic representation, mainly after analyses of Pub. 6, Mich. Geol. Surv., of the deeper mine waters, not much affected by recent circulation.

some waters found in granites, such as that of Vinal Haven, reported by Clapp, that of Georgia, reported by Fuller, and especially that of Storm King Crossing, analyzed by R. H. James, which Kemp gives me (Table V.), which may be residual granitic juice. But why should not the original ocean have had very much the composition of granitic juice? Whether granitic juice or ocean brine, they may fairly be considered to be connate and, anyhow, the prevalence of salt water at a relatively shallow depth appears in either case. That is all we are now interested in maintaining.

3. *Currents may be indicated by the changed character of the water and increase of Na even a long time after their circulation.*

If the above two conclusions are correct, it is quite obvious that this third one follows, since the circulation of relatively fresh waters into this salt zone will show in the character of the water. So, for instance, in the work at the Challenge (Fig. 1) location of the Copper Country, we find next the fault much lower chlorine than farther from it, though at the same distance from the surface and we generally find in the Calumet and Hecla conglomerate a greater proportion of sodium to calcium and, on the whole, a less salt water than in waters of similar depth where so great alteration has not taken place.

A review of the analyses given in this paper shows frequently the alteration of strata with water of different compositions, which may well be attributed to such circulation. If, then, waters are usually salty in less than 1,000 or 2,000 feet, the quite soft waters reported in Emmons tables from over 2,000 feet depth are partly, at least, due to circulation. Unfortunately, we know too little yet of the normal relative proportions of various waters to identify with certainty their constituents or to tell whether abnormal waters are due to juvenile volcanic waters finding their way up and pushing aside the connate waters or vadose waters finding their way down and pushing the connate waters before them or to vadose waters working their way up again through an inverted siphon, or to waters started into circulation by the heat of invading rocks.

Gautier thinks[1] that juvenile waters have sodium and alkaline bicarbonate and silicates and sulphides of heavy metals while carbonates of lime and magnesia, chlorides and sulphates, he regards as vadose. Lindgren tells me he thinks sodium salts, carbonates, sulphates, chlorides, with gases like CO_2, H_2S, etc., are magmatic, Cl_2 not. I think they are right as to sulphates, but as to carbonates I am not so sure. The question is to distinguish between ordinary desert waters started into upward circulation by the heat of igneous rocks and truly juvenile waters. The recent samples collected by Day and Shepherd[2] are presumably the

Gases CO_2	23.8–73.9 per cent.	in about 1,000 liters of gas	
CO	3.5– 4.6	water 100 c.c. +	
H_2	6.7–10.2	Na_2O	.0214–.031 gr.
N	11.8–63.3	K_2O	.0102–.011
SO_2	0. –12.8	CaO	.012 –.14
		Fe_2O_3, Al_2O_3	.08 –.01
		Cl	.22 –.206
		F	.565 –.492
		NH_3	.0018
		TiO_2	.005
		SO_2	.480 –.508

most authentic specimens of igneous emanations, but only confirm the table of volcanic emanation given by Lincoln,[3] in that they are at the same time acid, with the common acids CO_2, HCl, SO_2, etc., and reducing or deoxidizing with H, CO, H_2S, etc., present. Such emanations acting on rocks will give carbonates, sulphates and sulphides and chlorides, but ferric oxide will be reduced. But while oxidation is thus a sure sign of a vadose water, reduction may also take place in vadose water through organic matter. Even at the bottom of a deep stagnant pond, the waters may be as reducing as in the Black Sea, as shown by the work of the Wisconsin and Michigan state surveys. Waters

[1] Clarke, "Data of Geochemistry," U. S. G. S. Bull. 491, p. 202.

[2] Bull. G. S. A., Dec., 1913 (Vol. 24), p. 588–592.

[3] Economic Geology, Vol. 2, 1907, p. 262. See also Lindgren, "Mineral Deposits," pp. 56, 57, 60, 62, 106, 107; Clarke's "Data of Geochemistry," U. S. G. S. Bull. 491, pp. 182–187, 201–2.

coming up will, generally, be passing from a warmer to a cooler state. Whether they are circulating vadose waters which have found their way down and are now returning by an inverted siphon, as has until recently been supposed to be true in the case of the Saratoga wells,[1] or whether the water is, in part, for the first time reaching the surface, as Kemp now suggests for Saratoga, is obviously not easily determined. In either case, up-circulating waters will be likely to be more fully charged with soluble silica and any waters that attack the rock will tend to bring silica into solution and a heated alkaline desert water should probably pick up more than a juvenile hot emanation. Such waters as 22 and 23 of Emmons's tables, from the Comstock lode, are hot and heavily charged with silica and there are a good many other waters, like 27, which were not hot, but, nevertheless, in their high percentage of silica suggest that they have been hot and have cooled and that the circulation has been upward.

If we take waters which may be reasonably suspected to be juvenile waters, we find that with As, SO_4, B_4O_7, Fl, and similar substances, we do not find an amount of sodium chloride at all like that of the stagnant waters. The geyser waters (Table, Anal. 12) have only about as much Cl as SiO_2 (Clarke, p. 185), while the acid waters of volcanic origin (pp. 188, 189) (E. p. 188 and FG Y J of p. 189), that may have a lot of chlorine, *e. g.*, 11,009 HCl per liter, contain only a little Na and Ca. A mixture of such water with that of an alkali desert, *e. g.*, Lake Lahontan waters (Clarke, p. 148), might, however, make a fair parallel to a connate sea water of the stagnant zone, so far as the neutrality and the ratio of Na : Cl is concerned.

A striking feature of the juvenile and the vadose circulating waters seems to be a higher ratio of K : Na. K seems to be as readily attacked as Na, but more readily precipitated in sericite, glauconite, etc., and so seems less likely to remain in the stagnant or ocean water.

To sum up, then, relatively fresh water, with K high relative to Na and Na high relative to Cl, points to circulation. Extra

[1] Kemp, *Bull. N. Y. State Museum*, No. 159, p. 48.

oxygen or oxidizing actions point to downward circulation and so does Na abnormally high relative to Cl (*i. e.,* over .554). High silica and a high temperature point to upward circulation, and are, generally, associated with alkaline carbonates and sulphates, some (but an uncertain part) of the acid being perhaps juvenile.

4. *Up currents are likely to affect the country rock more than down.*

Let us consider what the pressure is upon the connate waters near the surface where the pressure is light. It is, as we know, very nearly that of a head of water from the surface to the depth where the waters in question are. But beyond that, we know that there is a tendency in open-grained rocks to have solution at points of pressure, the material from which may be precipitated again at points where the pressure is least. The grains of sand in a bed say 1,000 feet down will be sustaining the pressure of 1,000 feet of rock,—two or three times that which the water between the grains will sustain, provided the sandstone is self-sustaining. Therefore, there will be a tendency toward solution at the points of contact of material to be precipitated elsewhere, and as the rock is compacted together, slowly the water will sustain the whole weight of the rock as the connate water is forced out. The mean pressure upon the fluid between the grains will then vary between that of a column of rock and of a column of water of equivalent thickness, the difference depending upon many things,—partly upon what chance of escape the water has.

Suppose, then, there is a crack opened. In the crack, there is the hydrostatic head alone plus or minus a head equivalent to the velocity of any current down or up there may be. There will be a slow tendency, as the points of support of the individual cracks are dissolved and as the rock is made more and more compact, to have the interstitial water of this wall rock squeezed out, as from a sponge, into the crack. Therefore, we find, as we do, a tendency to have all the cracks in rocks filled up by growth from the side, because the water in these cracks is under a head that may well be 2½ times less than the pressure on the interstitial water.

Water coming into the crack where the head is less will tend to precipitate dissolved matter. Moreover, it may very well meet[1] in this crack with other fluids from other levels with varying pressures and perviosities that will promote precipitation. For instance, I have found a bed of hard cemented sand rock at the top of a bed of loose sand in drift deposits which were surmounted by clay. So, too, drillers often notice an extra hard and cemented layer just before encountering some flow, either of oil or gas or salt water. This extra hard layer, in cases known to me, was the Marshall sandstone cemented together by pyrite and I conceived that it might be due to a precipitation from waters containing the sulphates or bicarbonates of Fe by waters which acted to reduce the sulphate to sulphide; a reaction which stains a drill rope black. The circulation of water from the surface may, of course, in mountainous districts be fairly rapid. Usually if there is over a few feet of head, the velocity is quite great in the belt of open cracks and rapid circulation.

On the other hand, escaping vapors from igneous rocks may have all the pressure which the original igneous magma had and that must, at least, be the full pressure of the rock column down to the source of the magma, or if they are given off from the magma by a slow process of crystallization, there may be very considerable heads, quite independent of the depth. Thus, in that case, there is an impregnation of the country rock by the juvenile waters and propylitization or sericitization point to upward working waters.

5. *The water of lodes is rarely the normal connate water of the undisturbed country rock.*

In the rocks of the Copper Country, I have shown that the water of the lodes tends to contain more sodium than can be obtained by any mixture of the upper vadose waters or the deeper waters which seem to represent the less disturbed part of the rock. Again, if we turn to the analyses given by Emmons to illustrate enrichment by downward working waters (Tables VI.–IX.), we

[1] A small quantity even under a high head oozing in from a relatively impervious rock may not be crowded out by the flow of a larger quantity moving more rapidly with a greater initial head.

see, at once, striking differences between many of these waters and the ordinary waters to which we have called attention.

They have not as much chlorine as is very common in connate waters, by no means as commonly over 100 parts per million as in the undisturbed waters.

Another striking feature is an amount of silica expressed in two and sometimes three figures, which we find so often. The ratio of potassium to sodium in the mine waters is sometimes almost unity and much larger, generally, than in the stagnant waters. The acid which interests Emmons most (the SO_4) is, generally, far in excess of the chlorine, but, as his work shows, this is so liable to change that it is one of the most difficult by which to trace any general laws.

We find, also, in the analyses of mine waters given by Lindgren,[1] the same statements hold true, except for the Michigan waters and, even there, I am certain that near the lodes the water is fresher for a given depth and contains more Na.

6. *Systematic testing of water of the mines and that leached from drill cores of the country rock or flowing from drill holes may give suggestions worth while.*

The result of washing specimens of country rock has already been cited and the indications of the mine maters as compared with those of undisturbed strata distinctly suggest that a systematic testing of the rock in various directions should give some suggestions with regard to the general occurrence of currents.

For instance, it would seem that the chlorine should be relatively low along the main lines of circulation and should rise away from them as it does not only in the copper mines, but also in iron mines in Michigan.

In conclusion I want to express my thanks to Prof. F. W. Durkee, my colleague and your fellow member, for chemical help and also to Geo. Hooper, agent of the Victoria Mine.

I should ask him to sign as co-author, except that it would be hardly fair to drag him into a controversy that is not his.

[1] "Mineral Deposits," pp. 838–844.

WATER ANALYSES.

	1	2	3	4	5	6	7	8	9	10	11	12
												2,280
SO_4	19	75	234	110	448	416	477	406	593	1,350	833	H_2SO_4 43
Cl	4	702	45,178	176,027	5,652	1		7	843	10,823	542	HCl 6
CO_3	24			0				13			290	H_3 65
PO_4									tr			
B_4O_7				tr								92
Br			320	2,200								
Fl												H_2S 5
SiO_2	14	35		20		37	50	23	29	Al 70	10	90
K	11	414	3,837	411	154	3	2	7	11	70	24	8
Na				15,188	2,604	5	5	16	83	3,380	809	25
Li								tr				
Ca	13	91	22,201	86,478	827	20	30	151	512	2,404	158	40
Mg	2			20	119	5	6	28	103	760	67	21
Al						14	19	0			7	3
Mn				4					1			
Ni												
Co												
Cu			p.n.d. 8	16		28	11					
Zn						2	3		0			
Cd												
Fe″					4	71	89	2			1	
Fe‴						20	56					
Fe_2	4	30		10								
Al_2O_3												
Diff	3	3	330	11								
Org	n.d.											NH_4 652
Total solid	94	1,350	72.1	280,500							8,005	3,365

1. Mass Mine and Creek, Proc. L. S. M. I., Vol. XIII., p. 93.
2. S. Kearsarge, No. 1 Shaft, 9 level, *l. c.*, p. 820.
3. Isle Royale, No. 2 Shaft, 19 level, p. 823.
4. Quincy, 55 level, No. 6 Shaft, p. 794.
5. Storm King granite, 1,018 ft. deep, R. H. James.
6. Callaway Shaft, Ducktown water level, Emmons, *loc. cit.* No. 12.
7. Callaway Shaft, Ducktown, 37 ft. below No. 12, Emmons, No. 13.
8. Butte Green Mt. Mine, 2,200 ft. in fissure in granite, Emmons, No. 1.
9. Gagnon Mine, 1,125 ft. from shaft, Emmons No. 4.
10. Boston, 1750 ft. Boston Soc. N. Hist., 1875, p. 487.
11. Macomb W. W., Ill. St. Peters sandstone.
12. Devil's Inkpot, Yellowstone National Park. F. W. Clark, *loc. cit.*

THE DIFFERENTIATION OF A GRANITIC MAGMA AS SHOWN BY THE PARAGENESIS OF THE MINERALS OF THE HARNEY PEAK REGION, S. D.

VICTOR ZIEGLER.

That the association and formation of minerals is simply an expression of the physical condition at the time of their formation has been well emphasized by the work of Bischof, Lindgren, W. H. Emmons, Van Hise, and A. F. Rogers. Their work is sufficiently familiar to need no elaborate discussion. They have elucidated the principles of paragenesis in general, and have contributed paragenetic lists of minerals showing the associations of minerals and their dependence on certain physical conditions. This paper is an attempt to list the minerals of one district only, classifying them in a series of paragenetic groups. It is thought that such a list will be of general interest because of the wealth of minerals known from this district, the rarity of many of the minerals occurring here, and because geologic conditions are such as to make this district a mineralogical entity, differentiated sharply from, and entirely independent of the surrounding region. In addition the paragenetic table shows to an unusually complete degree the differentiation of a granitic magma.

The information embodied in this article was to a large extent acquired in the preparation of a bulletin on "The Minerals of the Black Hills" for the South Dakota State School of Mines and during the field work incidental to this, as well as a study of the "Ore Deposits of the Central Black Hills," undertaken for the same institution. Pres. C. C. O'Harra of the School of Mines has given much valuable information, while the publications of Blake,[1] Headden,[2] Hess[3] and Van Hise[4] have also been of great aid.

[1] Blake, W. P., U. S. G. S. Min. Res., 1883–1884, pp. 602–613; *Am. Jour. Sci.*, 3d series, XXVI., pp. 235; *Am. Jour. Sci.*, 3d series, XXVIII., pp. 340–341; *Am. Jour. Sci.*, 3d series, XXIX., p. 71; *T. A. I. M. E.*, XIII., pp. 691–

The central Black Hills consist of a core of Precambrian rocks chiefly slates, gneisses and schists, probably of Middle and Upper Huronion age, surrounded on all sides by the outward dipping parallel fringes of sedimentary strata, ranging in age from Cambrian to Pleistocene. The metamorphics are cut by granitic intrusions accompanied by many pegmatites all of which are also Precambrian in age. The intensity of the metamorphism increases as we approach the granite intrusions, which culminate in Harney Peak, now the highest point of the Black Hills uplift.

The chief metamorphic rocks in the immediate vicinity of Harney Peak are slates, phyllites, graywackes, actinolite schists, garnet schists, mica schists, staurolite schists, tourmaline schists, graphite schists, quartz schists, mica gneisses, amphibolites, and quartzites. As we recede from Harney Peak the slates become more abundant than the various schists. These are cut by a number of quartz veins which are older than the Harney Peak granite.

The Harney Peak granite is a soda rich granite, high in quartz and muscovite. It is very liable to show irregularities both of composition and of texture. Generally speaking, however, the granite is somewhat coarse in texture, and is rich in quartz and muscovite. Orthoclase, microcline and albite are the predominant feldspars, occasionally accompanied by minor amounts of oligoclase. Biotite is very rarely present and is the only iron bearing silicate (except garnet) that was noted in the granite. The granite usually shows also small grains or crystals of beryl, tourmaline, apatite, garnet, zircon and ore minerals. The high acidity, the presence of the minerals characterized by the miner-

696; *T. A. I. M. E.*, XIII., pp. 696–697; *Am. Jour. of Sci.*, 3d series, XLI., pp. 403–405.

[2] Headden, Wm. P., Colo. Sci. Soc., Proc., III., Pt. 3, pp. 323–346; Colo. Sci. Soc., Proc., III., Pt. 3, pp. 317–350; *Am. Jour. of Sci.*, 3d series, XLV., pp. 105–110; *Am. Jour. Sci.*, 3d series, XLVI., pp. 22–24; Colo. Sci. Soc., Proc., VIII., pp. 53–70; Colo. Sci. Soc., Proc., VIII., pp. 167–182; *Am. Jour. of Sci.*, 3d series, XLI., pp. 415–416.

[3] Van Hise, C. R., Geol. Soc. Am., Bull. I., pp. 203–244; U. S. G. S. 16th Ann. Rept., pp. 581–843.

[4] Hess, Frank L., U. S. G. S., Bull. 380, pp. 131–161. Hess, F. L., and Wells, R. C., *Am. Jour. Sci.*, 4th series, XXXI., p. 432.

alizers, the coarseness in grain, and the variability in mineral make-up, as well as geological conditions seem sufficient proof to the writer that the exposed portions of the granite represent only the marginal zone of a granite batholith, probably its upper surface laid bare by erosion. The granites proper are accompanied by a great series of pegmatites, characterized by extreme variability in composition and by very coarse crystallization, and by a series of more or less closely connected quartz veins.

The following genetic classification of minerals is adopted as best in keeping with geological conditions as outlined above:

MINERALS GENETICALLY CONNECTED WITH THE HARNEY PEAK GRANITE.
1. Minerals of the granite phase.
2. Minerals of the pegmatitic phase.
3. Minerals of the differentiated quartz veins.
4. Minerals in the contact zones.

MINERALS CHARACTERISTIC OF THE OLDER VEINS.

MINERALS CHARACTERISTIC OF THE METAMORPHIC ROCKS.
1. The original sediments.
2. The original igneous rocks.

MINERALS FORMED BY WEATHERING.
1. In granites and related rocks.
2. In the metamorphic rocks.

THE MINERALS IN PLACERS.

It is possible to make further subdivisions and this has been done where feasible and where sufficient information was available. In order that the minerals originating during the processes of differentiation may be more easily comprehended a table has been compiled giving the various minerals present in the region and the supposed genetic relationships of each. This table will be used as a basis for the following theoretical discussion.

THE MINERALS GENETICALLY CONNECTED WITH THE HARNEY PEAK GRANITE.

Minerals of the Granite Phase.—The sections 1 to 7 of the accompanying table show the various primary minerals which occur either in the Harney Peak granite, the pegmatites, or those quartz veins which undoubtedly represent quartzose differentiations from the granites and pegmatites. There are also included columns showing the mineral additions found in the contact zones formed

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Harney Peak.		Pegmatites.		Quartz Veins.				Met. Rocks.			Contact Zones.		
	Granite.		1. Phase.	2. Phase.	1. Phase.	2. Phase.	3. Phase.	Older Veins.	Schists and Slates.	Marble.	Amphibolites.	Granite.	Schists and Slates.	Placers.
	Typical.	Border Zone.	Mica-spodumene Type.	Amblygonite Type.	Tin Veins.	Tungsten Veins.	Miscellaneous.							
Actinolite	...	...	...	...	...	.....	...	.....	×	×	×	...	...	...
Albite	...	×	×	×	×	×	×	.....	×	...	...	...	...	...
Almandite	...	×	×	×	...	.....	×	.....	×	...	×	×	×	×
Altaite	...	...	...	...	...	.....	×	.....	.....	...	...	...	...	...
Amarantite	...	...	...	...	...	.....	...	S	S	...	...	...	...	...
Amblygonite	...	...	×	×	×	.....	...	.....	.....	...	...	...	...	...
Analcite	...	...	...	...	...	.....	...	.....	.....	...	S	...	...	...
Andalusite	...	...	...	×	×	.....	×	.....	×	...	...	...	×	...
Anglesite	...	...	...	...	...	.....	...	S	.....	...	...	...	...	...
Ankerite	...	...	...	...	...	.....	...	×	×	...	...	...	...	...
Anorthoclase	×	×	×	×	...	.....	...	.....	.....	...	...	...	...	...
Apatite	×	×	×	×	×	.....	...	.....	.....	...	×	×	×	×
Aragonite	...	...	...	...	...	.....	...	S	S	...	...	...	...	...
Argentite	...	...	...	...	...	.....	...	×	.....	...	...	...	...	...
Arsenolite	...	...	S	S	S	.....	...	S	S	...	...	...	...	...
Arsenopyrite	...	×	×	×	×	×	×	.....	×	...	...	×	×	...
Arsenostrengite	...	...	...	...	...	.....	...	.....	S	...	...	...	...	...
Atacamite	...	...	...	...	...	.....	...	S	S	...	...	...	...	...
Augite	...	...	...	...	...	.....	...	.....	.....	...	×	...	...	...
Autunite	...	...	×	×	...	.....	×	.....	.....	...	...	...	...	...
Azurite	...	...	...	...	...	.....	...	S	S	...	...	...	...	...
Barite	...	...	×	×	...	.....	×	.....	.....	...	...	...	...	...
Beryl	...	×	×	×	...	.....	...	.....	.....	...	...	...	...	×
Bindheimite	...	...	...	...	...	.....	...	S	.....	...	...	...	...	...
Biotite	×	...	×	×	×	.....	×	.....	×	...	×	...	...	×
Bismite	...	...	S	S	...	.....	...	S	.....	...	...	...	...	...
Bismuth	...	...	×	×	×	×	×	.....	.....	...	...	...	...	...
Bismuthinite	...	...	...	...	×	.....	×	.....	.....	...	...	...	...	...
Bismutite	...	...	S	S	...	.....	...	.....	.....	...	...	...	...	...
Cacoxenite	...	...	S	...	...	.....	...	.....	.....	...	...	...	...	...
Calamine	...	...	...	...	...	.....	...	S	.....	...	...	...	...	...
Calcite	...	...	...	...	...	.....	×	×S	×S	×	S	...	...	...
Cassiterite	...	×	×	×	×	×	...	.....	.....	...	...	×	×	×
Cerargyrite	...	...	...	...	...	.....	...	S	.....	...	...	...	...	...
Cerussite	...	...	...	...	...	.....	...	S	.....	...	...	...	...	...
Cervantite	...	...	...	...	...	.....	...	S	.....	...	...	...	...	...
Chalcanthite	...	...	...	...	...	.....	...	.....	S	...	...	...	...	...
Chalcedony	...	...	S	S	S	.....	...	S	S	...	S	...	...	...
Chalcocite	...	...	×	...	...	.....	...	.....	.....	...	...	...	...	...
Chalcopyrite	...	...	×	...	×	.....	×	×	×	...	...	...	...	...
Chlorite	...	...	...	...	...	.....	...	.....	×S	...	S	...	...	×
Chrysocolla	...	...	S	...	...	.....	...	.....	S	...	...	...	...	...
Cinnabar	...	...	...	...	...	.....	...	×?	.....	...	...	...	...	...
Claudetite	...	...	...	S	...	.....	...	.....	.....	...	...	...	...	...

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Harney Peak.		Pegmatites.		Quartz Veins.			Older Veins.	Met. Rocks.			Contact Zones.		Placers.
	Granite		1. Phase.	2. Phase.	1. Phase.	2. Phase.	3. Phase.		Schists and Slates.	Marble.	Amphibolites.	Granite.	Schists and Slates.	
	Typical.	Border Zone.	Mica-spodumene Type.	Amblygonite Type.	Tin Veins.	Tungsten Veins.	Miscellaneous.							
Columbite	...	X	X	X	X	X	...	...	...	...	...	X	...	X
Copiapite	...	...	...	...	...	...	...	S	S	...	...	...	...	...
Copper	...	...	...	...	...	...	...	...	S	...	...	...	...	...
Cummingtonite	...	...	...	...	...	...	...	...	X	...	...	...	...	...
Cuprite	...	...	...	...	...	...	...	...	S	...	...	...	...	...
Cuprocassiterite	...	...	S	...	...	...	...	...	...	...	...	...	...	...
Cymatolite	...	...	S	...	...	...	...	...	...	...	...	...	...	...
Diadochite	...	...	...	...	...	...	...	...	S	...	...	...	...	...
Diallage	...	...	...	...	...	...	...	...	...	...	X	...	...	...
Diopside	...	...	...	...	...	...	...	...	...	...	X	...	...	...
Dolomite	...	...	...	X	X	X	X	X	...	...	...	...	...	...
Dufrenite	...	...	S	S	...	...	...	...	...	...	...	...	...	...
Epidote	...	...	S	...	...	X	X	...	...	...	S	...	...	...
Fluorite	...	...	...	X	X	...	X	...	...	...	...	...	...	...
Galenite	...	...	X	...	...	...	X	X	...	...	...	...	...	...
Gold	...	...	...	X	...	X	X	X	X	...	...	...	...	X
Graphite	...	X	X	X	X	X	X	...	X	X	...	...	X	...
Greenockite?	...	...	...	...	...	...	...	X	...	...	...	...	...	...
Griphite	...	...	X	...	...	...	...	...	...	...	...	...	...	...
Grossularite	...	...	...	X	...	...	...	...	...	...	...	...	...	...
Gypsum	...	...	...	...	...	...	...	...	...	S	...	...	...	...
Halotrichite	...	...	...	...	...	...	...	...	...	S	...	...	...	...
Hematite	...	X	...	...	...	...	X	S	X	...	S	...	...	X
Hornblende	...	...	...	...	...	...	...	...	...	...	X	...	...	...
Hubnerite	...	...	...	...	...	X	...	...	...	...	...	...	...	...
Ilmenite	...	X	...	X	X	X	X	...	...	...	...	...	...	X
Jamesonite	...	...	...	...	...	...	...	X	...	...	...	...	...	...
Kalinite	...	...	...	...	...	...	...	...	S	...	...	...	...	...
Kaolinite	S	S	S	S	...	...	...	...	...	...	...	...	...	...
Labradorite	...	...	...	...	...	...	...	...	...	...	X	...	...	...
Lepidolite	...	X	X	X	X	...	...	...	...	...	...	...	...	...
Leucopyrite	...	...	X	X	X	X?	...	...	...	...	...	...	...	...
Liebenerite	...	...	S	...	...	...	...	...	...	...	...	...	...	...
Limonite	S	S	S	S	S	S	S	S	S	S	S	...	...	X
Lollingite	...	...	X	X	X	...	...	...	...	...	...	...	...	...
Magnetite	X	...	...	...	...	...	...	...	...	X	...	...	...	...
Malachite	...	...	S	...	...	...	...	S	S	...	...	...	...	...
Melanterite	...	...	...	...	...	...	...	...	S	...	...	...	...	...
Meneghinite	...	...	...	...	...	...	...	X	...	...	...	...	...	...
Microcline	X	X	X	X	...	...	...	...	...	...	...	...	...	X
Molybdenite	...	...	X	X	X	X	...	...	...	...	...	...	...	...
Molybdite	...	...	S	S	...	...	...	...	...	...	...	...	...	...
Monazite	...	...	X	X	...	...	...	...	...	...	...	...	...	X
Muscovite	X	X	X	X	X	X	X	X	X	...	...	X	X	X

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Harney Peak.		Pegmatites.		Quartz Veins.				Met. Rocks.			Contact Zones.		
	Granite.		1. Phase.	2. Phase.	1. Phase.	2. Phase.	3. Phase.	Older Veins.	Schists and Slates.	Marble.	Amphibolites.	Granite.	Schists and Slates.	Placers.
	Typical.	Border Zone.	Mica-spodumene Type.	Amblygonite Type.	Tin Veins	Tungsten Veins.	Miscellaneous.							
Natrolite	...	...	...	...	...	...	...	...	...	...	S	...	...	...
Niccolite	...	...	...	...	...	...	...	...	×	...	...	...	...	...
Oligoclase	×	×	×	×	...	...	...	...	...	...	×	...	...	...
Olivenite	...	...	S	...	...	...	...	...	...	...	...	...	...	...
Opal	...	...	S	S	...	...	...	...	S	...	...	...	...	...
Orthoclase	×	×	×	×	×	...	...	...	...	...	...	...	...	×
Ottrelite	...	...	...	...	...	...	...	×	...	...	...	...	...	...
Petalite	...	...	...	×	...	...	...	...	...	...	...	...	...	...
Phlogopite	...	...	...	...	...	...	...	...	...	×	...	...	...	...
Pickeringite	...	...	...	...	...	...	...	...	S	...	...	...	...	...
Purpurite	...	...	S	S	...	...	...	...	...	...	...	...	...	...
Pyrargyrite	...	...	...	...	...	...	...	S	...	...	...	...	...	...
Pyrite	...	...	...	×	...	×	×	×	×	...	×	...	...	...
Pyrolusite	...	...	S	S	...	...	S	S	...	...	...	...	...	...
Pyromorphite	...	...	...	...	...	...	...	S	...	...	...	...	...	...
Pyrope	...	...	...	...	...	...	...	...	...	...	...	...	×	...
Pyrrhotite	...	...	...	...	...	...	...	×	×	...	...	...	...	...
Quartz	×	×	×	×	×	×	×	×	×	...	×	×	×	×
Rubellite	...	...	...	×	...	...	...	...	...	...	...	...	...	...
Rutile	...	...	×?	...	...	×	...	×	×	...	...	...	...	...
Scheelite	...	...	...	S	...	×S	×	...	...	...	...	...	...	×
Scorodite	...	...	S	...	...	...	...	...	S	...	...	...	...	...
Sericite	S	...	S	S	×	×	...	...	...	...	...	×	...	...
Serpentine	...	...	S	...	...	...	...	...	...	×	...	...	...	...
Siderite	...	...	...	×	×	×	×	×	×S	×	S	...	...	...
Silver	...	...	...	...	...	...	...	S?	...	...	...	...	...	...
Smithsonite	...	...	...	...	...	...	S	S	...	...	...	...	...	...
Spessartite	...	...	×	×	...	...	...	...	...	...	...	...	...	×
Sphalerite	...	...	...	...	...	...	×	×	...	...	...	...	...	...
Spinel	...	...	×?	...	...	...	...	...	...	...	...	...	...	...
Spodumene	...	...	×	×	×	...	...	...	...	...	...	...	...	...
Stannite	...	...	×	...	...	...	...	...	...	...	...	...	...	...
Staurolite	...	...	...	...	...	...	...	...	...	...	...	...	×	×
Stibnite	...	...	...	...	...	...	×	×	...	...	...	...	...	...
Struverite	...	×	×	...	...	...	...	...	...	...	...	...	...	...
Sulphur	...	...	...	...	...	...	...	...	×	...	...	...	...	...
Talc	...	...	×	...	...	...	...	...	...	...	×	...	...	...
Tantalite	...	×	×	×	×	...	...	...	...	...	...	...	...	×
Tapiolite	...	×	×	×	...	...	...	...	...	...	...	...	...	...
Tellurite	...	...	...	...	...	...	...	S	...	...	...	...	...	...
Tenorite	...	...	...	...	...	...	...	×	×	...	...	...	...	...
Tetradymite	...	...	...	...	×	...	×	...	...	...	...	...	...	...
Titanite	×	×	×	...	...	...	...	...	...	...	...	...	...	...
Torbernite	...	...	×	×	...	...	×	...	...	...	...	...	...	...

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Harney Peak.		Pegmatites.		Quartz Veins.				Met. Rocks.			Contact Zones.		
	Granite.		1. Phase.	2. Phase.	1. Phase.	2. Phase.	3. Phase.	Older Veins.	Schists and Slates.	Marble.	Amphibolites.	Granite.	Schists and Slates.	Placers.
	Typical.	Border Zone.	Mica-spodumene Type.	Amblygonite Type.	Tin Veins.	Tungsten Veins.	Miscellaneous.							
Tourmaline	...	×	×	×	×	×	×	×	.....	...	...	×	×	×
Tremolite	...	...	...	...	...	.....	...	.....	×	×	...	...	...	...
Triphylite-Lithiophylite:														
Soda rich	...	...	×	...	...	.....	...	.....	.....	...	...	...	...	...
Soda poor	...	...	...	×	...	.....	...	.....	.....	...	...	...	...	...
Triplite	...	...	×	...	...	.....	...	.....	.....	...	...	...	...	...
Uraninite	...	...	×	×	...	.....	...	.....	.....	...	...	...	...	...
Vivianite	...	...	...	S	S	.....	...	.....	.....	...	...	...	...	...
Wad	...	...	S	S	...	.....	...	.....	.....	...	...	...	...	...
Willemite	...	...	...	...	...	.....	...	×?	.....	...	...	...	...	...
Wolframite	...	...	×	×	×	×	...	.....	.....	...	...	...	...	×
Zincite	...	...	...	...	...	.....	...	×?	.....	...	...	...	...	...
Zircon	×	×	×	×	...	.....	...	.....	.....	...	...	...	...	×
Zoisite	...	...	...	...	...	.....	...	.....	.....	×	S	...	...	...

(Note: Since the above went to press, there has come to the author's attention cyanite, which should be included under column 9. Cryolite has since been reported from pegmatite near Glendale. On account of the rarity of fluorine minerals, the author is reluctant to accept the determination until he has verified this occurrence.)

by the granite or pegmatite in the older rocks. The first seven columns also give us a chronological sequence for the crystallization of the various minerals from the magma, the mineral associations representing successively younger phases as we follow the columns to the right.

A granite near Custer was taken as representing in all probability most closely the Harney Peak magma. Its evenly granitoid texture, typical composition, and the absence of unusual accessory minerals lead to this conclusion. This granite is characterized by alkali feldspars (chiefly orthoclase, and in minor amounts microcline, anorthoclase, and oligoclase); both biotite and muscovite, with the former in excess; and probably 8 per cent. of quartz. The accessory minerals in the order of their importance are apatite, zircon, magnetite, and titanite.

By far the greater areas of granite exposed differ decidedly from this, and these the writer, for reasons already given, considers marginal zones of the batholith. This type of granite is coarser in crystallization, individual grains attaining a diameter occasionally of 6 inches, but averaging ½ to 1 inch. The main mineralogical change as will be seen from the table, is the enrichment in accessory minerals especially those carrying mineralizers. This enrichment is not uniform but quite sporadic. One group of accessories may characterize the granite in one place, while quite a different set may appear elsewhere. However, the main changes are as follows: Among the feldspars, albite appears and often in as great abundance as microcline and orthoclase. Muscovite becomes very prominent, while biotite is apparently absent. Quartz increases very much in abundance, rising up to 25 per cent. of the mass of the rock. Of the accessory minerals magnetite fails. A little light green lepidolite appears. Tourmaline (black and blue) becomes the most abundant, followed closely by apatite, almandite, zircon and beryl in minute grains. Titanite becomes rarer, while tin, niobium and tantalum minerals (cassiterite, strüverite, columbite, and tantalite) appear sporadically in rounded grains and minute crystals. Specular hematite, ilmenite and arsenopyrite appear in various localities in small amounts.

Minerals of the Pegmatitic Phase.—The pegmatites readily fall into two subdivisions. The mica-spodumene type and the amblygonite type. By far the majority of the dikes of the first class are located nearer to the center of the granites, and in their mineralogical composition are intermedite between the granite and the second type of pegmatites. They are hence considered to be the older phase of the pegmatites and are thought to represent an earlier segregation from the magma.

The mica-spodumene type of pegmatites differ from the marginal granite facies in coarseness of crystallization. They are "giant granites" in the true sense of the word. Orthoclase, microcline, and oligoclase, occur in blocks exhibiting the same orientation for as much as 5 and 6 feet. Tourmaline, apatite, mica and beryl attain a diameter of from 1 to 3 feet. Lepidolite

and albite occur in micaceous and lamellar aggregates up to 6 feet across. Spodumene has developed in log like crystals 2 to 5 feet in diameter and frequently 30 feet long, with an extreme length of 42 feet on record.

As has been indicated, the chief mineralogical change is one of quantity, but there is a notable increase in the variety of metallic accessory minerals. Quartz becomes the most prominent mineral, followed most commonly by feldspars, but in some cases by spodumene. Muscovite is usually next in importance, occasionally large flakes of biotite appear, while locally lepidolite occurs in bright green, brown, or colorless aggregates. Tourmaline is the most abundant and at the same time most persistent of the accessory minerals but is followed closely by phosphates, such as soda rich—lithiophylite-triphylite, dark blue apatite, triplite and griphite (a phosphate of MgFeNaLi restricted to the Black Hills). Autunite and torbernite occur as minute scales and incrustations on muscovite and tourmaline, respectively, in a great number of such dikes. Amblygonite occurs occasionally in small six-sided prismatic crystals. Monazite is rare. Beryl and spessartite are locally abundant in crystals from 6 inches to a foot in diameter. Almandite, graphite, melanite and titanite are of minor importance locally. Sulphates appear in the form of barite.

There is a decided increase among the metallic minerals. Cassiterite, columbite, tantalite, wolframite and ferberite form locally enriched shoots in a number of these dikes. Strüverite and tapiolite are more restricted but occur in a similar way. Spinel and bismuth are very rare. Sulphides and related compounds are locally represented by the following which are given in the order of importance: arsenopyrite (often abundant), leucopyrite, löllingite, molybdenite and very rarely stannite, galenite, chalcocite, and chalcopyrite.

The younger phase of pegmatites are also characterized by a coarse crystallization and a decided increase in the variety of minerals present. Spodumene, however, becomes less important, and true lithiophylite, amblygonite and lepidolite are the chief

lithium minerals. Albite is the most important feldspar. Quartz is very abundant, both in milky and rose varieties. Muscovite is next to quartz and feldspars in importance. Tourmaline and the phosphates (lithiophylite, triphylite, apatite, amblygonite and minute scales of autunite and torbernite) are about equal in importance. The metallic minerals stay about as before except that pyrite is added to the list of sulphides, that ilmenite reappears and that gold has been proven to be present by assays in several of these pegmatites. Fluorite has been found in small crystals in one pegmatite. Siderite and dolomite are of primary character in several, adding carbonates to the list. Petalite and uraninite are very rare. Andalusite becomes quite abundant in several such pegmatites, appearing in coarse, flesh red to slaty blue crystals and masses. Corundum has been reported, but although a careful lookout was kept for it in the field, none was found. A number of supposed corundum specimens transmitted to the School of Mines proved to be andalusite. For these reasons corundum is not included in the list.

Minerals of the Differentiated Quartz Veins.—The tin veins represent a later and more quartzose phase in the differentiation of the Harney Peak granite than the pegmatites. Their mineral composition as well as their occurrence in the field shows the close genetic relationship existing between them. By far the most abundant mineral in the tin veins is a milky pellucid quartz, accompanied by muscovite, and more or less graphite. Albite is quite frequently present in small amounts. Orthoclase occurs rarely. Tourmaline is quite frequently present in minute needles, especially along the walls. Dolomite and siderite become more common but are still somewhat rare. A flake of biotite is occasionally found as well as andalusite, amblygonite, and spodumene. Fluorite is exceedingly rare. Apatite is not unusual in microscopic crystals. Among the metallic minerals cassiterite is the most important, followed by columbite-tantalite, wolframite, arsenopyrite löllingite, molybdenite, and ilmenite. Bismuth, bismuthinite, and tetradymite occur in two such veins. Chalcopyrite was found in one. Texturally, there is a marked contrast

with the preceding. These veins are fine-grained, crystals rarely exceeding an inch in diameter, and are narrow, highly elongated lenses, while the pegmatites, especially the later phases, are rounded knobs or stocks.

There are several veins north of Hill City which are transitional to the tungsten veins and mineralogically are a composite of the two.

The tungsten veins again are chiefly milky to gray pellucid quartz, carrying fair amounts of muscovite and sericite, and frequently graphite. Feldspars and most accessory non-metallic minerals of tin veins, except dolomite and siderite, disappear. Epidote appears evidently as a primary constituent. Among the metallic minerals columbite-tantalite are very rare. Cassiterite becomes of minor importance. Arsenopyrite and ilmenite remain constant. Bismuth minerals are apparantly rarer. Pyrite reappears, followed again by gold (as shown by assays). Among the tungsten minerals wolframite, scheelite, huebnerite, and ferberite appear in the order given. Texturally these veins are similar to the tin veins.

There are also a series of quartzose veins in the district which on account of their geologic relationship as well as mineral composition are regarded as end phases in the pegmatitic differentiation. These are summarized under column 7. Just what their relationship is towards groups 5 and 6 it is probably impossible to determine definitely. The writer is inclined to think that they represent still later differentiation. He is led to this belief by the fact that in one case, such quartz veins occur as ladder veins in a narrow pegmatitic vein referable to group 5. In another case such a vein cuts across a dike of group 5. In others, no such comparisons can be made. Field relationship to the tungsten veins (group 6) cannot be determined, no tungsten veins occurring near them. These veins (of group 7) in barren portions are an exact replica of the tin-tungsten veins, but carry no feldspar. The occurrence of the bismuth minerals as well as torbernite and autunite, andalusite, tourmaline and scheelite seem to indicate some genetic relationship. The other minerals such as specular

hematite, ilmenite, altaite, gold, sylvanite, epidote, galena, sphalerite, barite, biotite, siderite, calcite, chalcopyrite, pyrite and stibnite are probably of no diagnostic value, although all, with the exception of altaite, stibnite, and sylvanite occur in some one of groups 1 to 6.

In summary then, we may state that the differentiation of the Harney Peak granitic magma leads to probably seven types of rocks. A typical granite representing the initial phase. At the borders this shows an enrichment in accessory minerals, especially those carrying mineralizers, a concentration of metallic minerals such as oxides and niobates, a loss of biotite and increase in muscovite. Graphite appears here, and is present in all six remaining phases. The pegmatitic facies can roughly be subdivided into two groups, both of which are characterized by an excessively coarse crystallization and by a notable increase in soda and lithia minerals, which in the older group tend to form silicates, while in the younger phase they appear to a large extent as phosphates. The niobium minerals reach their climax simultaneously with lithia minerals both as far as abundance and variety are concerned. Carbonates and sulphates appear. Sulphides and related compounds also seem to be present in greater abundance than before. The later pegmatite phase also shows the greater variety of mineral species.[1] Gold proved to be present upon assays of the milky quartz masses from the Dyke Lode. The next phase marks the climax of the tin occurrences. The great variety of minerals especially phosphates has disappeared. Silicates, except muscovite and tourmaline, are unusual. Niobium and tantalum minerals occur only rarely. Tungsten minerals first appear prominently. Probably 90 to 95 per cent. of the whole rock is SiO_2.

[1] There is good geological reason for considering these amblygonite pegmatites later differentiations than the mica-spodumene type. Thus the main body of the Peerless mine or the Hugo mine are of the mica-spodumene type of pegmatites; both, however, have been faulted and brecciated in the central portion and up through the fissures so developed have arisen the amblygonite bearing solutions. Beautiful slickensided surfaces are shown in the Peerless and along these the amblygonite is found. At the Hugo there is a huge shoot of milky quartz which marginally carries much brecciated material. It is in this central portion that the amblygonite occurs.

The sixth well-defined phase is marked by the climax of the tungsten minerals. Cassiterite is still present in some, but niobium minerals have practically disappeared. Tourmaline, muscovite, graphite are the only minerals of prominence that are still present. The presence of gold was proven by assays. The last phases appear to be of variable character and it cannot be definitely affirmed that the lead, zinc, bismuth, and gold content of the veins represent ultimate segregation from the magma rather than the result of leaching. Probabilities, however, point to this conclusion.

Under groups 12 and 13 are shown those minerals which are apparently added to contact zones when pegmatites or pegmatitic granites cut the older rocks. The mineral additions caused in granites by the crystallization of the pegmatites in contraction joints, are shown under 13; while those formed in the contact zones of schists or slates are shown under 14. In the first case the most noticeable change appears to be a loss of biotite, and the addition of quartz, sericite and muscovite. The minor accessory minerals also appear to be concentrated here to some extent. This is especially true of tourmaline. In the schists the mineralogic changes are very similar, resulting in a loss of basic minerals and an apparant substitution of quartz, muscovite and tourmaline as the most noticeable change.

The minerals of the veins of older age than the Harney Peak granite are shown under group 8. It is probably unnecessary to state that quite a series of veins each characterized by its own set of minerals are summarized here.

The minerals of the metamorphic rocks are given under columns 9, 10, and 11, which represent respectively those of schists and related rocks, marbles, and amphibolites. The marbles are very rare and only two exposures are known, neither of which the author had time to visit. A number of specimens from both localities are however available and from these the necessary data was obtained.

The minerals that owe their origin to weathering have been indicated under the various groups by the letter "s." This was

thought to be a more desirable arrangement than a separate column.

Column 14 shows the minerals found in placers. Those minerals resistant to weathering predominate, but as is to be expected under exceptional conditions others may become quite important. Thus a specimen of tetradymite was collected from placer diggings and sent to the author for identification.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

THE ORIGIN OF SECONDARY SILICATE ZONES.

DISCUSSION OF PAPER BY W. L. UGLOW.

Sir: In his original paper on the origin of secondary silicate zones at the contacts of intrusives with limestones,[1] Mr. Uglow divides the minerals of the contact zones into two groups. Group 1 contains garnet, epidote, diopside, tremolite and other silicates most abundant in these zones; group 2 contains in addition to quartz, muscovite, albite and the metallics only those minerals that contain "mineralizers." He then limits the phrase "secondary silicate zone" to the phase characterized by minerals of the first group (p. 26), and proceeds to argue that the minerals of this "secondary silicate" zone are the result of recrystallization of the impurities of the original limestone (p. 222 and p. 233). He admits that minerals containing such elements as boron, fluorine and beryllium involve contributions from igneous sources, but from a careful re-reading of his paper I am unable to find any indication that he attributes the formation of garnet, diopside, etc., to igneous emanations, and it was upon that point that I took issue with him.

In a recent reply to criticisms by Professor Kemp and myself, he says:

"The list of minerals in group 2 should of course be enlarged to include some garnets, pyroxenes, amphiboles, etc., which are sometimes

[1] ECON. GEOL., VIII., pp. 19–50 and 215–234.

the products of the second phase of contact action. Undoubtedly in the great number of cases of contact action that have been described, the two processes have varied greatly in their relative strength and influence. Indeed, when the second, or infiltration process, was exceedingly potent, the materials emitted may have largely replaced and so destroyed the results of the first process."

These two statements involve a great change from the contention of his first paper as I interpreted it. With the re-stated views that garnets, amphiboles, and similar minerals may be the result of both processes, and that the relative importance of the two processes may vary in different cases, I am in entire accord. In fact this is exactly the conclusion of my original discussion.

The specific point of difference now remaining between us is the interpretation of the analyses of contact zone material from the San Jose, Bisbee, White Knob, and other localities discussed in the original paper. In that article Mr. Uglow states that the "ratio of $SiO_2 : Al_2O_3 : Fe$ in the unaltered rock is very nearly identical with their ratio in the unaltered type" (p. 220). In reply to my criticism of that statement, he writes:

"*With respect to the differences shown by potash, soda, magnesia, lime, water, and carbon dioxide ratios,* there certainly is an approximate constancy in the silica, alumina, and iron ratios."

From the standpoint of the recrystallization hypothesis the bearing of this statement upon the disputed question of the origin of the secondary silicate zone is as follows: Lime, magnesia, alkalis, etc., are removed in the process of metamorphism in amounts depending upon their varying solubilities under varying conditions of combination, change in composition of leaching waters, etc.; therefore their ratios show great variation in the altered rock. Silica, iron and alumina in great part remain behind and are recystallized; therefore their ratios remain more nearly the same.

"It would indeed be a remarkable coincidence if the silica, iron, and alumina were each time added in almost exactly the same ratio as that in which they were present in the unaltered rock."

In view of the preceding, it seems evident that the essential point is not whether the silica, iron, and alumina ratios vary

more or less than other sets of ratios, but *whether or not they vary at all.* In my first discussion I showed that the ratios in question did exhibit a variation of from 20 to 700 per cent. I still believe that such a variation is appreciable, and that it does not accord with the hypothesis that the iron, alumina, and silica represent the original impurities of the limestone left in practically unchanged proportions. The fact that lime, magnesia, water, and carbon dioxide show greater differences means to me that the removal of these substances in the process of replacement or volatilization involved greater changes in the ratios than did the magmatic additions; it does not prove that these latter changes were not considerable.

We must remember also that the changes in the ratios are in *different directions,* in some cases the silica having increased relatively to the alumina and iron, in other instances the reverse being true. At Iron Springs the ratio of silica to alumina has *increased* nearly a third; in Hastings County the same ratio has *decreased* the same amount; at Iron Springs the ratio of alumina to iron has *decreased* over 50 per cent., while in Hastings County the same ratio shows a slight *increase.* The ratio $SiO_2/(Al_2O_3 + Fe_2O_3)$ varies as follows: Bisbee, an *increase* of about twenty five per cent.; White Knob, a *decrease* of over 60 per cent.; China cello, a *decrease* of 20 per cent.; San Jose, a slight *increase;* Morenci, a *decrease* of over 700 per cent. Therefore iron, silica and alumina in the metamorphosed rocks show not only a different ratio, but they show in some cases an increase of one constituent, and again an increase of another. I believe such a condition more easily explained on the hypothesis of magmatic additions in varying proportions than upon the re-crystallization hypothesis.

Mr. Uglow makes much of the fact that the analyses quoted are incomplete, or were not taken with the view of distinguishing between the first and second stages of metamorphism. What analyses of different samples *might* show is beside the point. The original paper maintained that as they stand these analyses indicate the re-crystallization hypothesis as the most favorable

explanation. It may also be urged that under the revised views stated by Mr. Uglow some of the discrepancies can be explained as due to two processes being important. That of course involves no progress, for it is admitted by all advocates of magmatic additions that whatever impurities were present in the limestone have gone to make up the contact silicates in part.

I disclaim all intention to be unduly controversial, particularly since Mr. Uglow has so courteously replied to my rather blunt criticisms of a very painstaking piece of work, but I cannot forego a reply to the implied accusation that I misinterpreted the original paper in assuming that it did not allow magmatic waters a part in the formation of garnet zones. In this connection Mr. Uglow quotes from his original paper as follows:

> "This view (recrystallization hypothesis) does not by any means involve a total absence of infiltrated material from the intrusive, but its advocates maintain that the so-called contact zone can be lithologically divided into two parts, one of which is formed by recrystallization in the early stages of metamorphism, and the other part by later addition of material in the way of emanations from the magma."

If he had continued this quotation to include the next sentence, he would have added:

> "The minerals which belong to the first class are those mentioned in the left hand column on pages 7 and 8, while those of the second class include, among others, those listed in the right hand column."

In view of the fact that garnet, epidote, pyroxene, and other common contact minerals were definitely included in the minerals of the first class, and nowhere mentioned as minerals of the second class, I believe that I was entirely justified in interpreting Mr. Uglow to mean that garnet, epidote and similar minerals are the result of recrystallization alone, and that only the minerals containing mineralizers or associated with minerals containing mineralizers belong to the second class. This belief was further strengthened by Mr. Uglow's treatment of the various districts. Localities that have become classic as instances of magmatic additions—if magmatic additions be conceded at all—were treated as most in accord with the recrystallization hypothesis.

C. A. STEWART.

SECONDARY SILICATE ZONE.

DISCUSSION OF PAPER BY W. L. UGLOW.

Sir: Mr. Uglow's letter in continuing the discussion of the interesting question of the formation of the lime-silicate contact zones, and their associated deposits of minerals, is expressed in the best of spirit and will be unreservedly welcomed by all to whom this subject has appealed. It is unfortunate that the controversial portion of his first paper was so prominent as to render too inconspicuous the very important points now more clearly brought out. Sympathizers with views which were pretty severely attacked, and, as it seemed to them, sometimes on rather far-fetched grounds, could hardly be blamed for coming to their defence.

All closely observant students of these phenomena have noted the succession of the minerals in time of formation. The line is not absolutely drawn between the silicates and the ores, but the contrast is clearly observable and the distinctions have been recorded by almost all who have written of the phenomena. The explanation of this succession as due to stages of different influence on the part of the intrusive mass, first of heat effects without pronounced emissions; and later of emissions with contributions, about whose relative importance and character we may still differ,—the explanation, one may repeat, is of great interest and is worthy of careful reflection and of trial application. Nevertheless, the objections on the chemical side, advanced by Dr. Stewart and the writer, seem still so difficult to meet, that one can hardly admit that they have been successfully overcome. Without repeating them here, they may be commended to those studying and interpreting the phenomena of contact metamorphism, as considerations not to be lightly overlooked.

J. F. KEMP.

THE ORIGIN OF THE "GARNET ZONES" AND ASSOCIATED ORE DEPOSITS.[1]

Sir: During the last fifteen years much attention has been given to the "contact metamorphic" ore deposits which mainly occur in limestone close to intrusive contacts. In general these deposits are characterized by the association of magnetite and simple sulphides with the so-called "contact metamorphic" silicates. These silicates comprise garnet, epidote, vesuvianite, tremolite, wollastonite, diopside, hedenbergite, ilvaite and many other rarer forms. The contact metamorphic zones contain also in places minerals with boron, fluorine and chlorine like axinite, tourmaline, danburite, fluorite and scapolite. There is also more or less quartz and coarsely recrystallized calcite. The simple sulphides embrace pyrite, pyrrhotite, chalcopyrite, galena, zincblende, more rarely arsenopyrite. On the whole, sulphantimonides and sulpharsenides are rare. Deposits of magnetite or chalcopyrite or of both are most common.

The deposits have an irregular or rudely tabular form, following main contacts, dike contacts or stratification planes; they rarely extend for more than 1,500 or 2,000 feet from the contact; far more commonly they only reach a distance of a few hundred feet from that surface. The deposits are usually formed by replacement of limestone, or allied calcareous rock. Apparently they are found both in relatively pure and in impure carbonate rock.

The deposits are geological bodies of a chemical and mineralogical character differing greatly from the adjoining intrusive rock and from the unaltered limestone. They are rich in silica and iron with more or less of lime, magnesia, alumina, sulphur and rarer metals like copper. The so-called contact metamorphic silicates which form the gangue usually are coextensive with the metallic minerals, though of course not necessarily with the merchantable ore. All opinions agree in holding the deposits of epigenetic origin, later than the enclosing limestone.

[1] Introduction to a discussion at the New York meeting of American Institute of Mining Engineers, 1914. Published through the courtesy of the author and of the American Institute of Mining Engineers.

Regarding the origin of the metals and the genesis of the ores there are several opinions.

1. There are those who see in these deposits the result of concentration of material contained in the intrusive rocks by means of hot circulating waters of atmospheric origin; the circulation established being upwards on the periphery of the hot mass.

"The heated ground water would be quite competent to do all that is ascribed to magmatic waters including the formation of lime silicate zones."[1]

Among the minority who still cling to this view I find Professor Lawson. The latter writing with his customary well sharpened pen describes the magmatic theory of these deposits as "one of the fashionable vagaries of our time, not entitled to serious respect as a scientifically established theory."[2] I am inclined to hope that Professor Lawson has already changed this view. If he has not I am sure he will before long, especially if he should undertake a somewhat careful study of a considerable number of the contact metamorphic deposits in the southwest and in Mexico.

In the first place these deposits are "high temperature" deposits. The character of the gangue minerals shows that they were formed at considerable depth—some well within the zone of fracture perhaps only 4,000 feet below the surface—others deep down in the region where fracturing must be considered impossible. In both cases the essential characteristics are the same. According to our best information the lowest temperature at which garnets, diopside, etc., may form is about 400° or 500° C. In view of the well-grounded attacks lately made upon the theory of the deep circulation of atmospheric waters it devolves upon the supporters of the view set forth under (1) to explain the possibility of such a circulation upward along the contact at temperatures of from 300° to 1000° C. The Daubree experiment will really not suffice any more as an explanation.[3]

[1] Lawson, A. C., Mining and Scientific Press, February 3, 1912.

[2] *Loc. cit.*

[3] Johnson, John, and Adams, L. H., "Observations on the Daubree Experiment and Capillarity in Relation to Certain Geologic Speculations," *Jour. Geology*, Vol. 22, 1913, pp. 1–15.

I shall try to make the real position of the leaching theory a little clearer: The metals, etc., were extracted from the intrusive rock, that is from a hot body having a temperature of from 500° to 1500°, and deposited in the adjacent, cooler sediments, say at temperatures from 300° to 1000° C. Consequently the circulation of the atmospheric waters would really take place in a lateral direction and not simply *along* the contact as maintained by Lawson. The silicates present in the contact zone prohibit the assumption of concentration at lower temperatures.

No one who has observed many deposits of this kind can fail to be impressed with the fact that the ores are generally found at limestone points projecting into the intrusive mass, or in slabs of limestone swimming in the igneous rock. It is difficult to see why the circulating atmospheric waters should seek such places by preference. In many deposits there is no evidence of fractures or paths which could have been followed by the water.

Inevitably, such a hydrothermal circulation as is suggested by Professor Lawson would result in a strong alteration of the intrusive. In many instances there is no such evidence of replacing solutions. Fresh granitic rock often borders the ore.

Mineralized later fractures may, however, cross these contact deposits and then the intrusive rock may be hydrothermally altered, but this does not prove that this is caused by atmospheric waters. It is clear, of course, that thermal metamorphism is not denied by Lawson; and he also admits a so-called "reactionary metamorphism wherein the changes are due to reaction between the encasing rocks and the materials emanating from the intruding mass."[1] Thus for instance he would class the hornfels of Clifton, and that from the Kristiania region as the result of thermal metamorphism. But the overlying limestone when it contained andradite and magnetite and sulphides would be a product of circulating atmospheric waters. Truly an odd position to defend!

It has been asserted that these deposits are exceptional cases, because they do not occur along all contacts or along the same contact. The answer to this is that the economically valuable

[1] *Loc. cit.*

deposits are exceptional but the *mineralization* is not, as one often can ascertain by carefully following one of these contacts.

2. There is another school, of which C. K. Leith is perhaps the most prominent exponent. These men do not by any means deny the actuality of emanations from the magma, but hold that the silicate gangue minerals are mainly the result of a recrystallization of constituents originally contained in the limestone, like calcium, magnesium, iron, aluminum and silica. This involves of course a great reduction of volume since the latter three constituents are usually subordinate in limestones, the removal of a great deal of material and a compression obliterating structures and textures. The additions from the magma are laid mainly to a late stage during which the silicates containing mineralizers and the iron ores were introduced. "The metallic minerals may be either direct contributions from the magma or hot water deposits resulting from the working over of the hot intrusives."[1] No statement is made as to the derivation of this water but atmospheric waters are probably meant.

Much effort has been expended in attempting to prove the first part of the proposition, namley the development of the silicates by a reduction of volume of the limestone amounting to 40 to 80 per cent. The last paper with this end in view has been contributed by W. L. Uglow,[2] who endeavors to show by comparison of analyses of fresh and altered limestones that the ratio of silica to alumina and ferric oxide is constant. The analytical material is evidently insufficient, especially as several of his analyses of "fresh" limestones already contain silicates. That no such constancy is shown has been clearly pointed out by C. A. Stewart.[3]

Few of the analyses have separate determinations of Fe and Al in the unaltered limestone. Were such determinations available I suspect that the non-constancy in the ratio Al : Fe would be still more apparent.[4]

[1] ECONOMIC GEOLOGY, Vol. 8, 1913, p. 26.
[2] ECONOMIC GEOLOGY, Vol. 8, 1913, Nos. 1 and 3.
[3] ECONOMIC GEOLOGY, Vol. 8, 1913, No. 5.
[4] I find that the analysis given by Mr. Uglow for the "Modoc limestone" at Clifton has been obtained by taking the average of the two analyses from

Mr. Uglow also attempts a general critique of the literature and theory of contact metamorphism deposits, but in this he is evidently handicapped by lack of field experience.

The main argument of the supposition of the "residuary crystallization" theory is that the impure limestones with much silica are the ones which yield the contact metamorphic silicates. This is of course largely a question of facts. Evidence that cannot easily be refuted has been introduced to show that the contact metamorphic silicates and the ores often form in very pure limestone. But it is conceded that they may also develop in impure limestone. According to the supporters of the residuary crystallization theory, a very large reduction of volume has been effected in either case, which of course would make the stratification a jumble near the contact. The expulsion of so much calcium and magnesium carbonate involves first a development of porosity and then a compression by the stresses from the intruding magmas. The reason why most silicate zones are composed of hard compact rocks is therefore that the porous rock has been strongly compressed. (In some cases one is tempted to add that the rocks, upon this theory, must have been principally pores.) Later, upon cooling, contraction fissures appeared and received some emanations from the magma or material concentrated by hot water from the intrusive rock.

I must here refer to the Washington Camp in Arizona, described by Professor Crosby. According to his statement the silicates and ore in the Pride of the West mine have been formed from an impure limestone. I investigated this occurrence carefully in 1909 with Mr. F. C. Schrader, of the U. S. Geological Survey, and was reluctantly compelled to adopt a different view. It seemed to me that a stratum of particularly pure limestone had here been replaced, lying between beds of markedly impure and siliceous limestone which have suffered little alteration.

That part of the pure bed which is converted into ore and silicates presents the unusual feature that the altered material con-

Modoc Mountain, which of course is correct, and one analysis, materially different, from Shannon Mountain, three miles distant. This is, to say the least, a curious proceeding.

tains some rather large druses, which are coated by fine quartz crystals. In this case, then, the pressure of the magma was not great enough to compress a drusy material into a compact mass.

It should be added that many of these silicate rocks as exposed at the surface appear porous and drusy but this is usually caused by the solution of interstitial and residuary calcite.

Thus far no conclusive field evidence has been introduced showing the compression demanded by the "residuary" theory. We owe probably the best and most careful examination of a metamorphic zone to Professor Barrell.[1] He concludes that in the outer metamorphic zone there must have been effected a considerable compression for which he, however, found no convincing field evidence; while the inner zone, in which additions from the magma seemed clearly demonstrated, showed no evidence of reduction in volume. Theoretically, according to Barrell there should be a slight expansion in this zone.

It is obviously impossible that structures and textures could be retained on the residuary crystallization theory. That such structures are in fact often retained has often been shown and I have particularly called attention to the preservation of fossils in greatly garnetized rocks at Tres Hermanas, New Mexico.

Mr. F. C. Calkins and Mr. B. S. Butler have recently completed careful investigations of contact zones at Phillipsburg, Montana, and San Francisco, Utah.[2] In both cases evidences of porosity or compression were sought for but not found.

It seems as if a careful microscopic study of limestones in all stages of recrystallization would convince anyone that no such wholesale reduction of volume has taken place. Delicate needles and prisms of amphibole or proxene or skeletal forms of garnets appear which are not disturbed or crushed by the metamorphism in more advanced stages. A part of the limestone may be replaced by quartz and both calcite and quartz are without disturbance traversed by a system of amphibole prisms.

The tendency of crystallization in skeleton forms leads to the so frequent development of residual calcite included in the sili-

[1] U. S. Geol. Survey, Prof. Paper 57, 1907.
[2] U. S. Geol. Survey, Prof. Papers 78 and 80, 1913.

cates. I can find little to contradict the conclusion that the metasomatism takes place by equal volumes and that there is practically no change in volume in the altered rock compared to the original rock.

The advocates of the residual crystallization theory reluctantly admit that boron, fluorine, etc., may have been introduced. Are they sure that these were the only elements introduced? It seems to me absolutely impossible to draw a line between the ordinary silicates and these containing mineralizers. Both are commonly intergrown showing practically contemporaneous origin. Take for instance the occurrence of axinite which so frequently has been overlooked, the brown massive mineral looking much like garnet.[1] Sulphur has equal right to be regarded as a mineralizer and from Day's and Shepherd's work at Kilauea[2] we know that even the surface lava gives off much more sulphur than fluorine and boron. Even if nothing more is admitted in the way of emanations it is clear that sulphides may result in the adjoining rocks. Has the old experiment been forgotten showing the development of magnetite in a limestone fragment immersed in molten basalt?

I do not intend to deny for an instant that the impurities in a limestone may be utilized in its subsequent recrystallization and I have noted the wollastonite developing at the contact of chert nodules and limestone as described by Crosby from Washington Camp, but I do insist that if it is admitted that a massive andradite garnet may form from a practically pure limestone no amount of diagrams can prove that the constituents of the garnet can be accounted for by residuary crystallization.

3. The view that accounts for the silicate minerals, and the minerals containing mineralizers, and the iron ores, and the sulphides by assuming that they are derived in large part from the emanations from the magma seems to me so plausible, so convincing and so fitting when the subject is regarded from a broad standpoint that I cannot help joining Kemp, Spurr, Goldschmidt and many others in advocating it. I believe thoroughly that iron, silica, various rarer metals, the mineralizers, to a smaller degree

[1] Schrader, F. C., U. S. Geol. Survey, Bull. 497.

[2] *Bull. Geol. Soc. Am.*, Vol. 24, pp. 573–606, 1913.

also alumina and the alkalies are thus contributed by the intrusive. The limestone and the intrusive emanations form a chemical system in which reactions of great intensity are proceeding. Sometimes there is also a vigorous interaction between the limestone and the intrusive as shown by the occasional development of epidote and garnet in the latter.

The emanations consisting of gases, water and volatile compounds in which the metals are probably carried as chlorides or fluorides, penetrate the limestone easily. In connection with this I wish to call your attention to some diagrams and mathematical calculations presented by Messrs. Leith and Uglow in which it is shown how excessively slow the diffusion of heat is from an intrusive contact. No doubt the calculations are correct but their presentation is an excellent instance of the danger of applying mathematics to geology. The diffused heat is as a matter of fact a feature of minor importance. The penetration of the emanations into the solid rocks is the main cause of the contact metamorphism. These emanations penetrate the suitable strata of limestone as if the latter were a sponge and they also travel rapidly on fissures and joints. Convection thus far outdistances diffusion. Every geologist who has studied contact metamorphism is well aware that certain beds, not unlike those above and below, show extraordinary selective power of recrystallization and mineralization. It is well known that some limestones are easily penetrable by oil, so that they may be rendered strongly translucent by such impregnation. If this can be effected at lower temperatures what would be the effect of emanations under tremendous pressure and temperature.

The principal differences among those who believe in the magmatic theory relate to the order of introduction of the various minerals. Some, like J. E. Spurr, hold that the development of silicates preceded the metallization as a more or less distinct stage and make of the latter a hydrothermal phenomenon taking place after the consolidation of the intrusive magma. Others see a rather continuous process in the metallization, holding that it began at the moment of irruption.

It has always seemed to me most difficult in this case to sepa-

rate metamorphism and metasomatism. I am inclined to minimize the purely thermal metamorphism and this opinion is strengthened by the extremely slow rate of diffusion of heat. On the other hand it is well known, for instance, through the work of F. C. Calkins[1] that the emanations, resulting in tourmaline and scapolite, spread long distance from the contacts. It is therefore probable that the metamorphism which so often extends for many thousand feet from the contact is primarily induced by the transmission through the pores, fractures and bedding planes of solutions emanating from the magma but mingled on their way with interstitial rock moisture. In fact, the slowness of the diffusion of heat positively compels such a view. The replacement will ordinarily proceed by equal volumes but where the movement of the solutions was extremely rapid drusy texture might result. All this is on supposition that the locality is in the zone of fracture. If it is definitely in the zone of flowage, the temperatures could normally be much higher and the difficulty of escape of the carbon dioxide would naturally be much greater. Hence the development of silicates would proceed at a very much slower rate, so slow indeed that porosity would become improbable and any replacement would proceed on the basis of equal volumes; any material dissolved would immediately be replaced by new minerals.

In the diffusion of emanations from the magma certain constituents would penetrate much further than others. Carbon dioxide and other gases would certainly penetrate much further than silica for instance.

There is unquestionably a certain sequence in the development of minerals in contact zones. Many observations seem to prove that emanation of sulphides and magnetite continue after the contact action, resulting in silicate rock is completed and finally hydrothermal action results.

The strong advocates of this view, among which J. E. Spurr is prominent, seem however to minimize unduly the earlier development of sulphides and magnetite. I have often had occasion to emphasize these early accessions which I think cannot be denied. The recent literature contains little to make a change of opinion

[1] U. S. Geol. Survey, Prof. Paper 78, 1913.

necessary. B. S. Butler,[1] for instance, says of the Frisco district, Utah, that "in general the minerals of the contact zone appear to have been formed at essentially the same time, though in places the metallic minerals have formed later than the silicates, as well as contemporaneously with them." T. Kato[2] describing the deposits at the Okufo mine, Japan, states that wollastonite is the oldest mineral and that it was formed by accessions of silica. He considers the earliest solutions to have been very siliceous. Next follow andradite with traces only of alumina; this is intergrown with vesuvianite. The sulphides were formed contemporaneously with the garnet or at the closing epoch of its deposition. Veinlets of chalcopyrite form the latest manifestation of metallization.

In conclusion, I would say that the most convincing argument in favor of the derivation of these deposits from emanations from the magma is not this or that single fact, but the great chain of circumstantial evidence which connects the contact metamorphic deposits with the high temperature veins on one hand (such as the cassiterite veins for instance) and the pegmatitic veins and dikes and concentrations in molten magmas on the other hand. In some cases evidence of this kind, with grading to ordinary veins, indicating lower temperatures, is offered in the vicinity of a single intrusion. If to this is added the direct evidence of emanations from the surface lavas, for instance of sulphur and fluorine from the Hawaiian volcanoes, the whole forms a well supported theory which should require respectful consideration even from those who would attribute a paramount rôle to the atmospheric waters.

WALDEMAR LINDGREN.

RECRYSTALLIZATION OF LIMESTONE AT IGNEOUS CONTACTS.[3]

At the outset I would like to make it clear that I do not enter this discussion in a controversial spirit, but in an attempt to contribute something helpful to an understanding of a difficult prob-

[1] U. S. Geol. Survey, Prof. Paper 80, 1913, p. 84.

[2] *Jour. Geol. Soc. Tokio*, Vol. 20, 1913, pp. 13–32.

[3] Read at meeting of Am. Inst. of Min. Eng., N. Y., Feb. 1914. Published through the courtesy of the author and of the Am. Inst. of Min. Eng.

lem. I have too high regard for the sterling quality of the work of the men who have studied this subject in detail to offer anything in the way of essential contradiction to their statements of fact. Difference of opinion arises from differing valuation of the possible alternative hypothesis which these facts suggest.

Some degree of recrystallization in limestone contact zones has been recognized by many investigators. Earlier investigators, for the most part, assigned an important, if not the most important, rôle to recrystallization in development of these zones. With the growing recognition of introduction of ores and gangue materials into the contact zone from igneous rocks through the medium of primary magmatic solutions, there has been a tendency to ascribe to this process most, if not all, of the chemical and mineralogical characteristics of the contact zone., This has involved a correspondingly diminished emphasis on recrystallization of substances already there as a factor in the process, and in some cases even the complete elimination of this hypothesis. From detailed study of a few contacts, casual observation of others, and a general familiarity with the literature, some of us have been led in recent years to raise the question whether the pendulum has not swung too far away from recrystallization toward direct introduction from igneous sources, and to argue for more recognition of the part played by recrystallization.[1] The inevitable sequence has been that those of us who have taken this view have been charged, at least by inference, with emphasizing recrystallization to the total exclusion of the alternative process. Scientists, like other men, like to classify and pigeon-hole views under simple and definite designations, leaving out qualifications which would tend to make the classification more difficult to state. This has made the problem seem more definite and simple, but has tended to obscure the fact that the disagreement is primarily not one relating to essential facts but one of emphasis. The relative importance of processes seems to vary greatly in different districts. Until many

[1] Barrell, Joseph, "Geology of the Marysville Mining District, Montana; a Study of Igneous Intrusion and Contact Metamorphism," Prof. Paper No. 57, U. S. Geol. Survey, 1907; Leith, C. K., and Harder, E. C., "The Iron Ores of the Iron Springs District, Southern Utah," Bull. No. 338, U. S. Geol. Survey, 1908.

more contacts have been carefully studied, agreement as to the relative importance of processes in general is perhaps not to be expected.

Evidences for recrystallization, briefly summarized and without qualification, are as follows:

1. So far as there is recrystallization it relates mainly to part of the silicate minerals and the residual carbonates of the contact zone. By no stretch can it explain the metallic minerals. The development of silicates from the lime or magnesia carbonates involves the elimination of all the carbon dioxide and some of the lime and magnesia with recrystallization into silicates of part of the lime and magnesia together with other impurities which may be present, such as silica, iron, kaolin, and other substances. In certain districts the composition of part of the silicate zone (usually the outer part) corresponds approximately to the composition of the original carbonate rock, minus carbon dioxide and a part of the lime and magnesia. No analyzed samples have shown exact correspondence. It would be difficult to find exact correspondence because of later replacements, because of original variation of beds, and because of difficulty of confining sampling only to the recrystallized zone, but in some cases there is a remarkable tendency toward the constancy of silica-alumina ratios in comparison of original limestones and the supposedly recrystallized phases. The ratio is not absolutely maintained but the variation in the silica-alumina ratio is slight as compared to the variations which are found in the parts of the contact zone in which materials have been clearly introduced. It would be remarkable if substances brought in at random from magmatic sources should approximate so closely the composition of residual impurities of limestone. A most striking case of this, which has been worked out quantitatively on a large scale, is the contact metamorphism of cherty iron carbonates by great masses of gabbro in the Lake Superior country. Here the iron-silica ratio of the altered phase corresponds almost exactly with that of the original carbonate rock, the change being merely an elimination of carbon dioxide. Analyses have been taken from many thousands of samples

brought up in drill cores and in continuous sections across the formation.[1]

2. Secondary silicates of contact zones have often been found to be localized along cherty beds or around fragments of chert in the carbonate. Again the Lake Superior region furnishes an illustration in that cores brought from a depth of many hundred feet, where there has been no chance of surface alteration, and at some distance from the intrusive, show the development of secondary iron silicates, principally grünerite, along contact of carbonate and siliceous layers, in a rock which is so dense there is little or no possibility for the introduction of these substances from without. The ratio of silica to iron has been almost exactly maintained. And yet these are clearly developed under influence of intrusives.

3. The similarity of secondary silicates in limestones and marbles far removed from igneous contacts to some of those developed at contacts is also suggestive evidence of recrystallization along contacts.

4. Elimination of carbon dioxide and lime is postulated under either hypothesis, "replacement" or "recrystallization." The natural consequence of elimination is recrystallization of the residual materials, whether or not these are supplemented by accessions from magmatic sources. There is no good *a priori* reason why accessions should always exactly balance elimination, especially when the physical conditions of intrusion are considered,—and there is no satisfactory quantitative proof that they have. Under physical conditions which have been supposed to attend the earlier stages of intrusion of a magma it is easy to conceive of pore spaces caused by elimination to be closed as fast as formed, thereby reducing volume, and, in fact, it is usual to conceive of the pressure actually being a factor in the elimination. Under the replacement hypothesis we find it necessary to assume that whatever the pressure conditions were, whether those tending to close up openings or not, the materials taken out and those introduced were delicately balanced in volume,

[1] Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," Mon. 52, U. S. Geol. Survey, 1911, p. 546.

that just enough is introduced in any one place to take the place of that which is left.

5. The reduction in volume required by the recrystallization hypothesis cannot in most cases be disproved. So far as original textures are retained, as they are in some districts, then it is possible to infer, rightly I think, that the volume has not been considerably reduced, and, therefore, that elimination has not taken place except by equivalent introduction of new materials. But the supposedly recrystallized substances are usually in a structurally amorphous zone which may well be the residual of an original mass many times greater. Opponents of the recrystallization hypothesis have argued that the necessary elimination of substances, and consequent reduction of volume, is too large to be reasonable. The reasonableness or unreasonableness of this is a difficult point to argue. It is largely a matter of personal opinion. To me it does not seem inherently improbable. Elimination is equally necessary to the alternative hypothesis of introduction of the materials from magmatic sources. Without elimination it is necessary to assume an enormous increase in volume to take care of enough new material to give an average composition of the contact phase.

6. Discrimination of two phases of contact metamorphism is essential to an interpretation of conditions of formation of contact zones.

Students of contact metamorphism may to much advantage study the mathematical theory of heat conduction as applied to an igneous contact. We are indebted to Professors Ingersoll and Zobel[1] for an illuminating discussion of the principles of heat flow from an igneous rock of given dimensions into surrounding limestone. Their conclusions, which seem to be well based on general physical principles, are especially interesting in showing the remarkably slow progress of a heat wave into the limestone. Quoting from Ingersoll's and Zobel's discussion of a hypothetical case:[2]

[1] Ingersoll, L. R., and Zobel, O. J., "An Introduction to Mathematical Theory of Heat Conduction with Engineering and Geological Applications," 1913. Ginn & Co.

[2] *Loc. cit.*, pp. 128–129

"The conclusions to be drawn from the curves are: first, that the cooling is a very slow process, occupying tens of thousands of years; second, that the boundary-surface temperature quickly falls to half[1] the initial value and then cools only slowly, and also that for a hundred or more years there is a large temperature gradient over only a few meters and a very slow progress of the heat wave; third, the maximum temperature in the limestone, or the crest (so to speak) of the heat wave, travels outward only a few centimeters a year. The mass behind it will then suffer a contraction as soon as it begins to cool, and the cracking and introduction of mineral-bearing material is doubtless a consequence of this."

Especially significant is the inference from the curves of heat flow that in advance of the heat wave the rock is tending to expand, therefore, to be compressed, whereas, following it during a long period of time there is contraction and the development of cracks. These conditions seem to favor two principal phases of contact metamorphism.

As the igneous mass advances into limestone it presumably is exerting mechanical pressure, judging by deformation at some contacts, and at the same time sending out heat into the surrounding rock, which, itself, increases the pressure. It is difficult to avoid the conclusion that for a time at least the adjacent rocks are under considerable pressure and that this pressure would favor elimination. It does not seem at all necessary or probable that under pressure this elimination should be immediately followed by introduction of other substances from the magma, or putting it in another way, that substances from the magma should always so closely follow elimination as to replace molecule by molecule the original materials and thereby prevent any reduction of volume. As the crest of the heat wave advances into the surrounding limestone, lower temperatures follow, with the result

[1] Strictly speaking, the initial temperature of the boundary surface would be somewhat higher than this; for the conductivity of hot igneous rock is considerably greater than that of the cold limestone although, in order to be able to handle the problem, we have had to consider their thermal constants as the same. The temperature of the boundary surface for the first hundred years or so could best be estimated from equation (49) of Art. 80. The error introduced by assuming the diffusivities to be the same becomes less and less as the cooling proceeds.

that there is contraction and the development of openings. This contraction may effect not only the limestone but the intrusive itself. Into such openings the magmatic solutions may freely enter, and there are deposited the ores and some of their gangue materials. At the same time these solutions may replace the materials of the surrounding rock to a greater or less extent.

That contact metamorphism of limestone has been accomplished in two successive phases has been pretty well proved at certain contacts. It seems probable that when attention is directed specifically to this feature it may be found at others. The first phase seems to be characterized by the production of an amorphous, homogeneous, silicate mass, not definitely associated with fissures. In some cases this is discriminated sharply from, in other cases it merges gradually into, a phase characterized by sulphides and other ore-bearing minerals with their gangue materials, which occur much more largely in fissures. These fissures may often be seen to traverse the silicate zone of the first phase. The minerals of the later phase, both because of their composition and because of evidence of their transportation, cannot be regarded as recrystallizations of materials in place. They afford evidences of introduction from magmatic sources.

The two phases of alteration may merge one into the other both in time and place. The later phase may be expected to obliterate to some extent the earlier phase. Ordinarily the later minerals differ from the earlier ones, but certain silicates, quartz, and other minerals, may be common to both.

I do not attempt to cite evidences in detail from specific localities. The limitation of this paper to fifteen minutes precludes this. My purpose is rather to outline the case for recrystallization. W. L. Uglow,[1] in a recent paper in ECONOMIC GEOLOGY, has cited evidences and references in some detail and in a forthcoming paper will cite more. I do not contend that all contacts

[1] Uglow, W. L., "A Review of the Existing Hypothesis on the Origin of the Secondary Silicate Zones at the Contacts of Intrusives with Limestones." Part I., ECON. GEOL., Vol. 8, 1913, pp. 19–50; Part II., ECON. GEOL., Vol. 8, 1913, pp. 215–234.

will be proved to show important recrystallization or even that all of the illustrations cited in Mr. Uglow's paper are valid ones. I hold only that recrystallization has been proved in enough places and to sufficient degree to warrant its citation as a usual accompaniment of the process of introduction of magmatic materials. In some cases it seems to be important. In others evidence of it is slight or absent, though in these cases it may be masked by the introduction of materials in the second phase of contact metamorphism. Its complete absence in the nature of the case is difficult to prove quantitatively. Advocates of the recrystallization hypothesis have not, so far as I know, held that it was sufficient to explain all contact phenomena. They have offered it only as an explanation of one phase of contact alteration. Failure to consider this hypothesis involves failure to consider the possibilities of a two phase alteration which seems to me to be the probable key to much contact metamorphism. With the majority of economic geologists, I recognize the conspicuous evidence of the introduction of magmatic materials. My plea is that this hypothesis be not magnified to the exclusion of the recrystallization hypothesis. Quantitative studies of contacts based on adequate sampling have unfortunately been rare. Without them, conclusions can be only qualitative and not exclusive.

REVIEWS

Analyses of Coal in the United States. By N. W. LORD, ET AL. Bureau of Mines, Bull. 22, 1200 pp., 1913.

The most valuable publication of the year for the user, dealer, and exploiter of coal in the United States is Bulletin 22 of the Bureau of Mines. This bulletin makes no pretense of presenting new ideas on the composition of coal, but it gives in brief tabular form almost all of the analyses of coal that have been made by the United States Geological Survey and the Bureau of Mines from the beginning of the coal-testing work at the St. Louis exposition on July 1, 1904, to June 30, 1910. It also contains descriptions of the samples, the methods of sampling and analysis, and the apparatus used in the chemical laboratory.

The volume contains 3,740 analyses of samples collected in the following states:

Alabama	108	Kansas	21	Pennsylvania	419
Alaska	82	Kentucky	63	Rhode Island	13
Arizona	2	Maryland	69	South Dakota	2
Arkansas	65	Michigan	4	Tennessee	37
California	7	Missouri	130	Texas	19
Colorado	363	Montana	164	Utah	69
Georgia	3	New Mexico	57	Virginia	64
Idaho	1	North Dakota	31	Washington	283
Illinois	125	Ohio	48	West Virginia	1004
Indiana	67	Oklahoma	47	Wyoming	337
Iowa	18	Oregon	18		

These samples were collected by members of the Bureau of Mines in connection with their work of testing coal or in special studies of waste in mining, and by the geologists of the Geological Survey during their examination of coal fields in various parts of the country for the purpose of determining the coal resources and for classifying the public land. As the coal in many of the fields thus examined is not being mined in a commercial way, it has been practically impossible to obtain unweathered coal for analysis. In such cases the results given in the table are below what they should have been were it possible to secure fresh coal. In almost all cases such samples are marked as weathered and they should be taken at their face value.

Each analysis is given in three forms and many of these made early in this period are given in four forms. They are as follows: (1) Sample

as received at the laboratory, (2) moisture-free sample, (3) moisture-and-ash free sample, and, in a few cases (4) moisture, ash and sulphur-free sample. Form No. 1 is supposed to be satisfactory for all ordinary uses, such as the comparison of one coal with another to determine which is the better fuel. Form 2 is for the use of the mechanical engineer and forms 3 and 4 for those who deal with or wish to compare the actual coal substance free from its various impurities.

Form 1 serves very well for comparison of fuels in the high-grade coals of the east whose moisture content is generally less than 5 per cent., but when applied to low-grade coal and lignite having moisture contents of from 10 to 40 per cent., it is a very different matter and the analysis of the sample as it comes from the mine may show much or little moisture, depending largely upon the condition of the mine. In the laboratory the actual analysis is made of the sample, after it has been "air-dried" or dried in an oven at a temperature of 30° to 35° C. in a current of warm air until the weight of the sample remains constant. This form of analysis is not given in Bulletin 22, but in most cases the air-drying loss is stated so that the analysis may be recalculated by anyone desiring to use it.

The chief objection to the use of the air-dry form is that the air-drying loss as it has been determined in the past is extremely variable. This is well illustrated by the analysis of a North Dakota lignite as given on page 143. The moisture in two mine samples and the air-drying loss are as follows: No. 1971, moisture 42.06 per cent., air-drying loss 35.6 per cent.; No. 1972, moisture 42.81 per cent., air-drying loss 33.9 per cent. A carload of lignite from the same mine shipped to St. Louis (No. 2289) gave moisture 32.64 per cent. and an air-drying loss of only 10.4 per cent. Manifestly direct comparison of these three analyses in the air-dry form should not be made. The difference in the air-drying loss in the mine and car samples is to be explained by the fact that the carload of lignite shipped to St. Louis was dumped on the ground and lay several weeks before it was analyzed. The lignite had weathered so that it would not give up readily its loosely held moisture. The reviewer maintains, however, that when strictly fresh coal or lignite is secured, the results expressed in the air-dry form are strictly comparable and approach more nearly the commercial output than any other form. Weathered samples should not be used for analysis except in emergency cases and then the results should not be compared with results obtained from fresh material.

The disinclination by weathered coals to part with the loosely held moisture can be used as a criterion for determining which are fresh and which are weathered, and this is an all important distinction to make. For instance, if a subbituminous coal with a moisture content of 15 per cent. only loses 2 or 3 per cent. on air-drying it is safe to conclude with-

out further evidence that it is weathered, and the same may be said of bituminous coals, but of course the difference will be much smaller in the high-grade coals.

The reviewer has had an occasion to check over many of the analyses given in this bulletin, and so far has found only a few serious errors. In general, the arrangement is good and any particular analysis or the analyses of samples from a particular mine or field are easily found.

Altogether the bulletin is a most commendable report and contains the greatest number of analyses of coal that have ever been made by any one organization on samples collected in a systematic manner and analyzed under practically identical laboratory conditions. It will serve as an invaluable reference book to those persons interested in any way in the coals of the United States and Alaska.

MARIUS R. CAMPBELL.

Introduction to the Study of Igneous Rocks. By GEORGE IRVING FINLAY, Ph.D. Published by McGraw-Hill Book Company, Inc., New York, 1913.

This volume is a convenient size for carrying in the pocket; it is well bound in a handsome cover of flexible red morocco. The printing is excellent although some of the illustrations, especially Plate I., which is a color chart of birefringences, are unsatisfactory. The book contains 228 small pages, two colored plates, and a number of inserted tables.

In so small a volume the author has attempted to cover the whole field of Petrology—a Herculean task. The scope of the book can be best judged from the titles of its nine chapters. An introductory chapter on "The Qualitative Classification of Igneous Rocks" covers six pages; "The Determination of the Igneous Rocks in Hand Specimens" occupies nine pages; "The Movement of Light in Crystals," 29 pages; "The Identification of the Essential Minerals of Igneous Rocks," 45 pages; and "The Description of the Accessory Minerals of Igneous Rocks," eight pages. Nineteen pages are devoted to "The Igneous Rock Types," 27 to "The Varietal Rocks Related to the Type Rocks," and six to "Methods of Describing Rocks," which follows the textural terms as proposed by the authors of the Quantitative Classification. The last chapter of 74 pages is entitled "Outline of the Quantitative Classification of Igneous Rocks—Examples of the Calculation of the Norm—Tables to Facilitate the Calculation of the Norm."

The treatment of the subject is strikingly condensed rather than elementary; a treatment more suited perhaps to an abstract than to an elementary text-book. Notwithstanding the extreme brevity of the treatment of the various subjects, there are fewer inaccuracies and misleading statements than might be expected.

The reviewer takes this occasion to protest against a tendency in scientific education which is illustrated by this volume—the tendency to "cram" the student's mind with the largest possible amount of condensed information and to teach him in a mechanical way the routine of scientific research. This tendency to give a "practical education," avoiding "theory" as superfluous, is deplorable enough for the engineer; it is doubly so for the scientist. It may give to a man the maximum of efficiency during the very early years of his work, but it certainly does not best prepare him for a long career of original work of high quality.

ESPER S. LARSEN.

SCIENTIFIC NOTES AND NEWS[1]

T. T. READ, of New York, was a recent visitor in Washington.

PROF. J. A. UDDEN, of the University of Texas, visited Washington in March.

E. L. JONES, JR., of the U. S. Geological Survey, has left Washington to examine and classify, as to their mineral character, the lands of the Colorado River and Yama Indian Reservations. Arizona.

WILLIAM J. MILLER, for nine years professor of geology in Hamilton College, has accepted the appointment as head of the Department of Geology in Smith College, Northampton, Mass. His new duties begin in September, 1914.

THE FOLLOWING PAPERS have been presented at recent meetings of the Geological Society, of Washington: F. L. Hess, "A Hypothesis for the Origin of the Carnotite Deposits of Utah and Colorado"; E. T. Wherry, "The Occurrence of Carnotite in Eastern Pennsylvania"; H. G. Ferguson, "Auriferous Pocket Deposits of the Klamath Mountains, California."

D. F. HIGGINS, who devoted the season of 1913 to the preparation of a topographic and geologic map of the mining area of the Suan District, Korea, and a study of the geological structures of gold-copper-bismuth ores for the Seoul Mining Company, is now making geologic studies in China. His address is Peking, China, care of the American Legation.

PLANS FOR A PROPOSED EXPERIMENT STATION to cost five hundred thousand dollars for the housing of the United States

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

Bureau of Mines have been completed and approved by the commission appointed by Congress for that purpose. The buildings when erected will be adapted for the carrying on of the mine safety work and other investigations in which the Bureau of Mines is interested.

At the Engineering Congress to be held in San Francisco in 1915, a volume will be distributed embodying a series of articles on the design and construction of the Panama Canal. Among the chapters of this volume will be one entitled "The Geology of the Panama Canal Zone." Those desiring to send subscriptions for the assistance of the Engineering Congress are requested to do so as early as possible. Subscriptions should be sent to E. J. Dupuy, Foxcroft Building, San Francisco, California.

Messrs. Frederick G. Clapp and Myron L. Fuller, of the Associated Geological Engineers, Pittsburgh, are at present engaged in the examination of the northern parts of Chili and Shensi provinces in China for petroleum for the Standard Oil Company. An agreement was entered into between the Chinese Government and the Standard Oil Company in February for the development of the Chili and Shensi oil fields, and Messrs. Clapp and Fuller were in the field within a week after the signing of the agreement.

The Mining Bureau of the Ministry of Agriculture and Commerce of the Republic of China has engaged four foreigners and two Chinese, Messrs. Kwang Chung-kwang and Li Shih-wei, as mining advisers, with a view to developing the mineral resources of the country. Ex-Premier Hsiung Shih-ling has been asked to take charge of the petroleum resources of China, which duty is to include the making of the necessary inventories of the resources and the negotiating with foreigners and Chinese for their development.

ERRATA.

Figures 1 to 7 inclusive in the paper on "The oxidized zinc ores of the Tintic district, Utah," by G. F. Loughlin, printed in Vol. IX., No. 1, of ECONOMIC GEOLOGY, were printed without the author having an opportunity to examine their proofs and correcting their obviously wrong positions. The dips of the limestone beds represented in figures 1 to 5 inclusive should have been from 20° to 25° to the right. Figure 6 should have been printed at 45° to its present position, the right end of the figure moving down and thus giving a dip of 25° to 30° to the limestone beds at the right side of the figure. Figure 7 should have been printed at 90° to its present position, so that the right side of the figure would have been the bottom.

The percentage of zinc in calamine on page 4, which was incorrectly given as 61.8 per cent., should be 54.2 per cent.